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Multiresource Management of Ponderosa Pine Forests

Nov 14 - 16, 1989
Flagstaff, Arizona

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Multiresource Management of Ponderosa Pine Forests

Nov. 14 - 16, 1989
Flagstaff, Arizona

Technical Coordinators:

Aregai Tecle, W. Wallace Covington
Northern Arizona University

R. H. Hamre
Rocky Mountain Forest and Range Experiment Station

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Preface

It is our hope that this conference will be the first in a series of conferences which seek to call together natural resource managers, resource specialists, academicians, agency researchers, and concerned publics to focus on improving integrated ecosystem management of forest lands. For far too long there has been an unhealthy split among many of us. This split stems in part from the fact that each of these groups has a different set of assumptions and goals for management of forest resources. We have witnessed over the past 10 years an increasing propensity of individuals from each of these groups to prejudge individuals of the other groups, discounting what they have to say, simply because they are members of the other group. Isn't this bigotry? Its effect is just as debilitating to natural resource issues as it has been in other human enterprises.

Such a situation is simply no longer affordable. We must develop attitudes of mutual respect and cooperation to bring together the best available knowledge and procedures to generate the optimum management regimes for our public natural resources. Decisions we make today will determine the biological legacy we leave for many generations. We owe it to them and to ourselves to work cooperatively to make the very best decisions that we can, and to document the results of management activities in such a manner that those who follow can learn from our successes as well as from our mistakes. Toward this end, we must learn not only from conventional scientific research, but also from the wealth of knowledge of all of us who are interested in forest land management and from experiential opportunities afforded by whole-system manipulations by managers. Conferences such as this one are a step toward facilitating this learning.

The conference served as a forum for discussing current issues, concerns, opportunities, and procedures in multiresource management of ponderosa pine forests. As such it was able to draw together managers, resource specialists, Forest Service field personnel, representatives of various interest groups, as well as research and development scientists interested in implementing multiresource forest management. The end product of the conference is the publication of these proceedings.

Except for the first two papers – the keynote address and the paper titled *Research Needs in the Southwest Ponderosa Pine Type*, which constitute the conference highlights – the papers in these proceedings are grouped into six themes: (1) areal distribution, and growth of ponderosa pine forests; (2) factors affecting ponderosa pine forest resource outputs; (3) forest diseases, environmental pollutants, and other stresses, (4) wildlife habitat concerns; (5) modeling and integrating environmental and public concerns in ponderosa pine forest resource management, and (6) multiresource management, decision support systems and expert systems. Each of these six parts of the proceedings is preceded by a brief comment by the Session Moderator.

To facilitate rapid publication of the proceedings, the papers were submitted in camera-ready format by the authors. Authors are therefore fully responsible for the accuracy of their papers. The opinions expressed by the authors may not reflect those of the Forest Service, U.S. Department of Agriculture.

W. Wallace Covington
R. H. Hamre
Aregai Tecle

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Beaver Creek and Multiresource Management Forestry¹

Kel Fox and Lawrence D. Garrett²

Abstract.--The emergence of multiresource forest management in the Southwest scientific forestry community is related to the U.S. Forest Service research efforts on the Beaver Creek Experimental Area and later teaching and research efforts at the NAU School of Forestry. A brief history is provided on the evaluation of the Beaver Creek Project and its contribution to multiresource forest management science and practice in the Southwest.

As you can see from the program, Dean Garrett and I are conducting an experiment--giving one talk in two parts. I am leading off, setting the table and providing the hors d'oeuvres. Dave will serve the main course. Together we will be charting some of the history that leads to today's conference on multiresource management.

It begins with the Barr Report, so named for a University of Arizona professor. His directive was to see if the watersheds of the Salt and Verde Rivers were producing as much water as they could and should be producing.

Barr was an agricultural economist by trade, and knew relatively little about the products of the watersheds--trees, water, animals, and so forth. But he knew how to put together a team of experts who could find the answers. He brought men like Hal Wilm to the project. Then dean of the prestigious Syracuse School of Forestry, one of the nation's foremost forestry hydrologists, and a veteran of the first-ever experiment in increasing water yield at Wagon Wheel Gap in Colorado. From the

United States Forest Service he signed on Marvin Hoover, who had earned his spurs at Caveata and Fraser. Dudley Love, who later taught at this university, was included, and so was Bob Humphrey, nationally known for his research on range. And many others of equal ability joined the effort.

The contributions of these experts were refined into a document called "Recovering Rainfall." People soon forgot that catchy title, and referred to it simply as the "Barr Report." The report was optimistic. Yes, more water could be made to flow into the dams so important to the Salt River Valley, including Phoenix. How? By making modifications in existing understory and overstory management direction on the state's watersheds.

For example, clear cut small to medium sized patches in the mixed conifer forest. It will then produce more water, and--get this--more feed for deer and elk, because grass will replace trees in the openings created by the harvest.

To sum up, by reducing tree densities, man could add to his supply of water and the forest could carry more four-legged creatures, both wildlife and livestock.

Here then, was one of the first suggestions of multiresource management. Do something to one resource, in this case timber, and it's going to have an effect on several other resources. That

¹Paper presented at the Multiresource Management of Ponderosa Pine Forest Conference, Flagstaff, ARizona, November 14-16, 1989.

²Kel Fox is a rancher and technical advisor to the Arizona Lands Commission; Lawrence D. Garrett is Dean of NAU School of Forestry.

is a simplified summation of what multiresource management is all about.

The Barr Report received mixed reviews, some for, some against. But there were enough of us who believed in it to organize an effort to put its theories into practice. That was the genesis of the Arizona Water Resources Committee (AWRC), a group of private citizens formed for the express purpose of persuading the public land management agencies to adopt the report's suggestions.

Before that could be done, however, the agencies, notably the Forest Service, which controlled most of the watersheds in the study report, insisted the recommendations be tried under field conditions before putting them in the manual.

The Water Resources Committee eagerly embraced the idea and offered to help obtain the financing to make it a reality. Thus, over the next 20 years AWRC, as it became known, raised more than \$10,000,000 for watershed and multiresource management research. At the peak of this effort, there were research projects ongoing in 10 of Arizona's 14 counties.

The centerpiece of this research was a project called "Beaver Creek," located only a few miles from where we are sitting this morning. Though limited to ponderosa pine and pinyon juniper types, Beaver Creek grew so fast it soon overshadowed sometimes older projects examining mixed conifer, chaparral, and phreatophytes.

With a network of good, cinder roads, it was soon playing host to thousands of visitors annually, many of them scientists from foreign countries. To be sure, its emphasis, especially in the early years, was on enhanced water yield. But, from the very beginning, there were studies on what experimental harvests of pine were doing to other resources.

A good example was Watershed No. 9, where the pine was harvested in alternating strips 60 yards wide. Yes, these experiments demonstrated that they could produce more water, but the experiments were directed at a larger question. If these practices were applied to the entire Coconino Forest, what would be the effect on the supply of timber in 1990 or in the year 2,000? And how many additional cows and elk would be supported in the grassed-over

strips? What was the effect on fire prevention? And so forth.

Beaver Creek went up like a skyrocket. I feel many great accomplishments came from its programs. Most important, it was one of the ignited fires that has spread to today's concept of multiresource forest management.

For the full story of what it means to the science of multiresource management, we now turn to its last and best-known director: Dr. David Garrett.

Thank you, Kel.

I am David Garrett, and this keynote address is being delivered by Kel and I for two reasons. First and foremost, because the concepts of multiresource forest management in ponderosa pine were not initiated by scientists alone, such as myself, but also by city managers, hunters, and ranchers like Kel Fox.

Second, because Kel is right, Beaver Creek was a significant contributor to multiresource forestry in the Southwest. And, since Kel Fox was instrumental in starting Beaver Creek and I was instrumental in closing it, it seems only fitting that both of us get a chance to revisit it.

Beaver Creek was one of the leading large watershed experiment areas in the 1960's and 1970's, which included Caweeta, Hubbard Brook, and Fraser. However, as Kel mentioned, it had a scientific twist that was different. It attempted to investigate the interactive impacts of tree harvest, grazing, road construction, prescribed fire, etc. on a stream of forest resources; first water yield, sediment, and range, but as it progressed, the resource list grew to include small and large mammals, birds, wildlife habitat, recreation, scenic beauty, tree growth, forest litter, as well as others.

I don't mean to imply that scientific efforts at research watersheds such as Caweeta, Hubbard Brook and others did not focus on the ecosystem and its interaction. They did. However, the mission at Beaver Creek was different, in that it was strongly oriented to addressing forest resource interaction from a multiresource management perspective. Its research was focused toward management application.

The Beaver Creek Watershed Research Area was managed under U.S. Forest Service Rocky Mountain Research Unit 1654, known officially as the "Multiresource Management Evaluation Project" and unofficially as the "Beaver Creek Project." The official title captures the full intent of the research effort.

Led by a Project Director named Harry Brown, the first efforts were to develop individual resource projection models for several resources. These included timber growth, water yield, sediment production, wildlife habitat, forage production, scenic beauty, snow melt, and several others (Brown et al. 1974).

Much of the research that today guides individual resource management in Arizona was derived from university and U.S. Forest Service studies in the Beaver Creek Program. This includes management guidelines for wildlife, recreation, water, range, timber, sediment, prescribed fire, slash disposal, etc.

During the 1970's the Beaver Creek Project attempted to interrelate the impacts of differing resources on one another over time. Interdisciplinary resource specialists designed integrated multiresource sampling procedures and applied them to studies of several resources on a given watershed.

By the late 1970's there was a growing concern nationally that foresters didn't really know the state of the resources on National Forest, BLM, and other federal lands. Further, the general public was suspect that federal lands were not truly being managed well for all forest multiresources. As a result, the 1974 RPA, and the 1976 NFMA and FLPMA mandated multiresource management on all federal forest lands (Wilkinson and Anderson 1987).

Work was beginning on a complex linear programming model, that would later be called FORPLAN and become the central computer model for resolving multiresource planning alternatives at the National Forest level (Jameson et al. 1982). The future of forest management was rapidly becoming focused in legislation, policy and field management activity. The direction would be integrated multiresource forest management.

The scientists at Beaver Creek felt they could respond to the new direction with a method for multiresource analysis; a system model. Systems analysis was not new. Leading scientists, including Lotka and Odum as well as others had stressed the importance of systems science (Lotka 1956, Odum 1983).

However, the effort proposed at Beaver Creek was a forest systems management model. In some ways, the concept was similar to that being advanced by C. S. Holling and his associates at the University of British Columbia, called Adaptive Environmental Management (Holling 1978).

Documenting the extensive data base from Beaver Creek, and development of the forest system management model, ECOSIM, was the last research I and the Beaver Creek scientists completed before closing the infamous project (Rogers et al. 1984).

Today, eight years after closure of Beaver Creek, the focused southwest effort toward multiresource forestry science is at Northern Arizona University. However, NAU's current stature actually results from 15 years of effort.

In 1973, while Beaver Creek efforts were at their peak, NAU School of Forestry launched the first undergraduate forestry program in integrated multiresource forest management in the United States. It was a team taught three semester immersion program; quite progressive for its time.

In 1985, the School launched a special MultiResource Management (MRM) program at the masters level and in 1986 it launched a mission research program in MRM to support academic efforts.

In 1991 the School expects to have the most comprehensive effort in the United States in MRM, including BS, MS and Ph.D. degree programs, a mission research program, and a specialized Native American program.

Would I say that the Beaver Creek Program was the most influential factor causing NAU School of Forestry to pursue a multiresource forest management emphasis? No, I would not say that. Dr. Minor and the faculty at NAU were watching a national direction in forestry that continues to this day. Beaver Creek, however, was a strong part of that direction in the Southwest.

This week, at this conference, we will focus on accomplishments we have made to better understand the multiresource management of Ponderosa Pine. I applaud the effort by the School of Forestry faculty, the many sponsors, and speakers and attendees. Hopefully, it will be the first of many efforts to follow.

Having involved myself in this special management and science area for a decade now, I feel compelled to comment on two aspects of the endeavor as we begin the conference.

- Why do we need to involve ourselves with multiresource management science?
- Can we expect to effectively implement this direction?

The response to the first question can be found in many professional papers. Writings clearly reveal that this planet is a large ecosystem of interacting physical, biotic, social, economic, political and managerial resources and forces. Since man could reason, great minds have understood this. However, the resource base seemed so immense and so forgiving, that mankind accessed individual resources with limited regard for impacts to others.

Today, in forestry and natural resources, laws and social pressure demand that we incorporate a comprehensive understanding of all impacts from a management action, before the action is implemented. Although I sympathize with many regarding process weaknesses in the National Forest Management Act and other legislation that mandates this direction, I am convinced that on the whole, these laws embody the appropriate direction for proper resource management.

Issues such as global warming and the greenhouse effect best characterize the necessity to approach forest management from a complete holistic system concept. Ignoring physical, biotic, political, social, economic or management aspects of the problem will result in, at best, partial solutions.

And, our second question, can we expect to effectively implement this direction.

Educational, scientific, and management writings also document that

comprehensive system approaches are possible. They are also difficult, expensive, not easily understood, and therefore meet with a lot of resistance.

Yet, integration of forestry teaching methods, curriculum and disciplines have been accomplished at least partially in several forestry schools. At NAU we have found we can effectively integrate our entire curriculum. More schools are increasing their efforts to integrate parts of their curriculums.

Integration of system concepts in forest research seems more easily incorporated into current institutions. However, difficulties do exist. For example; university research normally rewards individual accomplishment, and, in fact, success often results from being a specialist in a very narrow field.

In federal and state agencies, both funding mechanisms and administrative direction create difficulties with integrated multiresource research approaches. Projects are generally organized and funded along single resource lines, are often administratively and physically separate, and generally report to differing line and staff managers.

As a result, only a handful of research projects with a multiresource management mission were ever created within the United States Forest Service. In academics, a few programs have also been developed, mostly as a result of large outside contracts. However, a multiresource forest research program developed as a school's central mission, with state funds, such as at NAU, is rare.

In the area of management, the U.S. Forest Service "Integrated Resource Management Program" (IRM) is still the most successful on the ground application of this philosophy (Jameson et al. 1982). The USFS is organized in a manner that permits rapid implementation. That is, both the budget process and management process support the direction. Although budgets are allocated by resource area, all resource areas and budgets are under control of the district ranger. Further, the ranger also controls an interdisciplinary group of specialists to implement IRM.

A final note. Although good approaches to MRM exist in teaching,

research and management, and are growing in numbers, the science is still young. Hopefully, this conference, and efforts to follow will greatly advance this science.

LITERATURE CITED

- Brown, Harry E., Malcus B. Baker, Jr., James J. Rogers, et al. 1974. Opportunities for increasing water yields and other multiple use values on ponderosa pine forest lands. USDA Forest Service Research Paper RM-129; 36 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.
- Holling, C.S. 1978. Adaptive Environmental Assessment and Management. John Wiley and Sons. New York.
- Jameson, Donald A., Mary Ann Dohn Moore and Pamela J. Case. 1982. Principles of Land and Resource Management Planning. Land Management Planning Office, U.S.D.A. Forest Service. Washington, D.C.
- Lotka, A.J. 1956. Elements of mathematical biology. Dover, New York. 465 pp.
- Odum, H.T. 1983. Systems Ecology. Wiley Interscience, New York. 644 p.
- Rogers, James J., Joseph M. Prosser, Lawrence D. Garrett, and Michael G. Ryan. 1984. ECOSIM: System for Projecting Multiresource Outputs under Alternative Forest Management Regimes. Administrative Report. Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Ft. Collins, CO.
- Wilkinson, Charles F. and Michael Anderson. 1987. Land and Resource Planning in the National Forests. Island Press, Washington, D.C.

Research Needs in the Southwest Ponderosa Pine Type¹

Lawrence D. Garrett, W. Wallace Covington, and Aregai Tecle²

Abstract.--Research needs for the ponderosa pine/Arizona fescue ecotype of Arizona and the greater southwest is discussed relative to trends in national and regional forest resource demands. National and regional demands on most forest resources are expected to increase. Critical resource demands in the Southwest will involve water, recreation, wildlife, and timber. Research is needed to better understand: the basic ecological interrelationships of forest resources; probable long term implications and cumulative impacts of changing ecologies; long term multi-resource flows from differing silvicultural regimes; impacts of improved utilization of standing timber inventories; improved multiresource management practices; and biodiversities under different managed and nonmanaged forest regimes.

INTRODUCTION

Ponderosa pine is a geographically dispersed conifer, indigenous to all states west of Colorado (Little 1979). The species is prized for its quality wood, which has versatility in framework, sheathing, subflooring, siding, window sash, doors, interior trim, pulp, poles, and timbers. The extensive ponderosa pine ecosystem of the Southwest also provides other critically important resources to the Southwest, including wildlife, fisheries, watershed, recreation, and forage.

The focus of this paper relates to research needs in the southwest

ponderosa pine type, more specifically the ponderosa pine/Arizona fescue ecotype of Arizona, New Mexico, and parts of Utah and Colorado (Schubert 1974). Although part of what will be recommended may also be appropriate to other areas, it is not the intent of this paper to make any recommendations for areas outside of the Southwest.

Schubert, in 1974, characterized the state-of-art silvicultural knowledge about this species. He also related the importance of understanding impacts of selected silvicultural methods on other resources. Brown and others (1974) discussed the implications of selected ponderosa pine silvicultural methods on many forest resources, including wildlife habitat, timber growth and yield, scenic quality, water, forage production, and environmental concerns such as sediment yield.

Other writers have investigated specific aspects of the ponderosa pine ecosystem. Ffolliott and Hanson (1968) developed relationships for snowpack development and melt. Baker (1986) provided analysis of long term annual water and sediment yields and expected water and sediment yields under differing silvicultural practices. Minor (1964) and Larson (1975) characterized growth and yield opportunities in southwest Ponderosa Pine in the developed model

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²Lawrence D. Garrett is Dean and Professor of Forest Economics, W. Wallace Covington is Professor of Forest Ecology, and Aregai Tecle is Assistant Professor of Systems Hydrology, School of Forestry, Northern Arizona University.

PIPO and in site-index curves. Daniel and Boster (1976) characterized near view scenic values of differing overstory and understory management regimes. Patton (1978), Balda and Masters (1980), Cunningham and Balda (1980), and others have contributed to a greater understanding of wildlife habitat relationships in this pine type. Clary (1975) contributed toward understanding forb, grass, and shrub response to differing silvicultural treatments. Sackett (1979, 1980) and Covington and Sackett (1984) have characterized conditions of fire ecology and impacts of prescribed fire. Many other authors have also contributed to understanding individual and joint resource relationships.

Rogers et al. (1984) developed a comprehensive ponderosa pine ecosystem simulator, ECOSIM, which utilized the above research as well as research of many other authors outside the Southwest. A number of individual resource models are linked, to simulate over time the response of the forest multiresources to management actions such as timber harvest, road construction, watershed improvements, and wildlife habitat improvements (Tecle and others 1988).

In referencing the current literature on southwest ponderosa pine, much is captured from research conducted on the Beaver Creek Experimental Area, a 275,000 acre watershed in central Arizona (Garrett 1985). This area lies on basaltic derived soils that are shallower, and not as productive as limestone derived soils found in the eastern mountain region of Arizona, along the Mogollon Rim.

Extensive stands of ponderosa pine in the Southwest exist on limestone soils on which minimal research has been accomplished. These soils are more productive than basaltic derived soils and would be expected to have better yields in all resource areas, such as wildlife, timber, range, etc. (Schubert 1974).

Further, considerable ponderosa pine forests exist in New Mexico, but have received limited research attention when compared to areas in Arizona. These forests are subject to similar demands, but respond to differing natural and human impacts. Similar statements could be made for ponderosa pine ecosystems in southern Utah and Colorado.

Today the extensive ponderosa pine

forest of the Southwest must respond to more complex managerial, political, social, and economic stimuli than they have ever had to in history. The issues of public needs and desires, environmental constraints, and resource conflicts will continue as growing forces in defining management direction, and therefore future research direction.

DEFINING FOREST RESOURCE DEMAND

To define future research needs, we should examine where this nation and the Southwest are heading as regards forest resource use, policy, and management. We also need to overview proposed research direction by other writers, to determine how our research needs in the Southwest are supported by and reflected in national direction.

Expected general trends on the nation's public and private forest lands, especially public lands, are as follows (USDA 1989a):

- The area of timber land in the United States will continue to decline. Public lands will decline another 21 million acres by 2040. Total demand for both hardwood and softwood timber in the U.S. and abroad will increase significantly over the next five decades, especially as regards fiber based products such as pulp and structural panels. Pressure will exist to increase total harvests in the United States. Real timber prices will also increase.

Pressure for greater timber harvests in the Southwest will also increase due to the condition of the resource base, the growing southwest market, and harvest trends in the greater Rocky Mountain Region.

- In general, water is in plentiful supply in the United States, although its distribution as related to agriculture, industry, and population centers does cause difficulties. Most of the difficulties relate to western United States' water supplies, which have been and will continue to be scarce in relation to demand. Water quality is becoming a greater issue, especially as regards nonpoint sources of pollution. Demand for water in the Rocky Mountain Region has increased at twice the rate as the North and Pacific Coast Regions. Water

shortages are projected for the lower and upper Colorado River, the Rio Grande Basin, the Great Basin, and California by the year 2040.

Outdoor recreation will increase in the future as population increases. Use will shift from long vacations to shorter vacations. People will recreate more often, however, they will probably travel shorter distances to access recreation sites. Free access to private lands will continue to decline and associated private land recreation fees will increase. Increased use will occur on public lands. Income growth will increase demand for more costly forms of recreation such as downhill skiing and boating. Growth in wilderness use will stabilize, and possibly decline, as growth in use of wilderness per capita slows due to population age and recreation time becomes more focused around weekends.

The national trends in increased recreation use of public lands are especially appropriate for the Southwest, where population centers are concentrated and expanding rapidly. The relative concentration of population and recreation areas will result in increased vehicular access problems. The greatest impacts will be on those recreation areas and forests adjacent to or near the large metropolitan areas, such as Tucson, Phoenix, Albuquerque, and Los Angeles. Recreation use will continue to diversify, with significant weekend and holiday intensity in all areas. Recreation related to cultural resources will increase as will conflicts related to this use. In general, heavy recreation demand areas will involve water related recreation opportunities. Creating access for an increasing population will become problematic for already heavily impacted areas such as the Salt river impoundments, Grand Canyon, Tonto National Forest, and Colorado River.

Future total demand in the United States for red meat will continue to increase along with the growth in population, with per capita consumption remaining approximately level. Forage supplies from public lands are expected to remain fairly constant over the next several

decades. An increasing supply of forage will be sought from private lands, due to continued multiple use conflicts on public lands. Private land quality will continue to decrease.

In the Southwest, most forage for livestock is derived from public lands, due to the minor acreages available in private ownership. Range demand will increase slightly. Multiple use conflicts regarding range on public lands will continue. This is especially true in riparian zones where degradation from grazing continues to be a problem, and in critical wildlife zones where competition from livestock reduces wildlife management capabilities.

- Demand for energy minerals, metallic minerals, and industrial minerals will increase as population increases. Minerals generally exist on a worldwide market where sufficient supplies are available to limit major price rises, except in energy minerals.

Most of the U.S. coal reserves lie under forest lands in the Appalachian region and northern great plains and most of the metallic minerals lie under forest and range lands in the central and southern Rocky Mountain regions. In the Southwest, metallic minerals will continue to be developed on federal lands as well as some energy minerals. For example, coal, oil and gas, phosphate, molybdenum and precious metals are expected to continue to be mined. Environmental concerns will result in increased conflict. A critical need will exist to determine the impacts of cumulative effects.

In general, the southern Rocky Mountain forest region of the United States will have to respond over the next five decades to similar consumptive patterns of the rest of the United States. However, because the southwest population is expanding more rapidly, and the region already has extensive multiple use, multiresource management conflicts will become major issues in determining planned use.

There will be a continuing need to access public range for livestock use, but livestock/wildlife and livestock/riparian zone conflicts must be resolved. Recreation may become the greatest single resource concern as

population increases and existing recreation areas exceed carrying capacity. Water will be an acute problem and forest and woodland watersheds will be looked to for increased supplies of quality water. Water will also be looked to for increased recreation opportunity, making riparian zones a high conflict area due to their importance for wildlife and fish, humans, livestock, and downstream water use. High quality ponderosa pine timber will continue to be demanded over the next five decades for commercial wood products.

CHARACTERIZING SOUTHWEST FORESTRY RESEARCH NEEDS

As noted above, characterization of present and future demands on forest lands across the United States in effect, captures many demands expected for the southwest region. It is critical that research responds to these near term management problems facing the region. It is also critical that research looks beyond these immediate management issues to discover other opportunities and/or information that can be utilized on future issues and/or problems yet to surface.

A recent report of the USDA Forest Service, the National Association of Professional Forestry Schools and Colleges and the USDA Cooperative State Research Service, listed four general goals for forestry research in the 1990's (USDA 1989a). These are also compatible with forest industry research goals. Together the groups involved account for over 95% of forestry research conducted in the United States. Listed goals are to:

1. Increase the productivity of the forests, and their associated multiresources such as water, recreation opportunity, wildlife habitat, and range resource,
2. Expand domestic and foreign markets for forest products, including primary processed and secondary processed products,
3. Improve the management of forests and associated resources to insure appropriate integration of all forest resource outputs in the best management practice, and
4. Enhance protection of the forest resource base to assure biodiversity and long term

ecological stability of the forest ecosystem including forest atmospheric interaction, fire, insects and disease, fisheries, wildlife, TES plants and animals, and water and soil.

We would like to take each one individually, and select a focus that we think is critical to the Southwest.

Increased Productivity of Forests and Associated Resources

Within this goal, we think the Southwest must be concerned in two particular areas; understanding the basic ecological processes of the ponderosa pine ecosystem and gaining better knowledge of the cumulative effects of management.

In basic ecological process research we need to approach the forest as a natural ecosystem under constant man-imposed or natural intervention. We must be able to isolate various processes and factors that are important to sustaining an individual resource, and also those that link it to other resources and characterize the importance of the linkages. For example, what are the interdependent processes by which wildlife are linked to other wildlife and the general forest environment to sustain appropriate energy levels? What are the methods by which water moves through surface and subsurface forest environments to plants, in-stream flows and impoundments? What are the intricacies of the processes, and how are these processes linked to and important for sustaining other resources?

And, second, we must understand with effective research, the cumulative impacts of management. By definition, understanding linked processes and driving factors will help us in this effort. We need to develop models of large forest ecosystems and watersheds that help predict long term effects of forest management practices on forest structure and function.

Critical in this effort are improved survey techniques for gaining multiresource data that have both time and space dependence. Without these improved data it will be most difficult to characterize natural interactive processes across land forms, or monitor cumulative impacts of departures from these natural processes under management action. These data will be critical to effective analysis and model building.

Also of critical importance, system models for modeling biophysical interactions among resources and processes over both time and space must be developed and evaluated.

Discriminant analysis, stochastic processes, Delphi technique, linear programming, and data handling tools such as geographic information systems must be brought to bear on the issue. The systems developed will be very helpful in determining interdependencies among forest resources in space and time, in defining research needs, and in formulating less complex multiresource management models, desperately needed by forest planners and managers.

Expand Domestic and Foreign Markets for Forest Products

We do not feel that the Southwest will look toward foreign markets as an outlet for its wood products. However, a significant share of the wood products manufactured in the region are currently shipped to other regions. As the southwest market grows along with U.S. and world markets, opportunities will exist to market more wood products within the region.

Research to increase our current timber utilization level would assist greatly in extending and making more profitable the current resource base. Research on utilization of the timber base in new product outlets that provide higher value added to the region would also be of great benefit.

The five to eleven inch diameter class of ponderosa pine needs to be investigated for appropriate commercial utilization opportunities. Currently insufficient public funds are available to precommercially thin these stands. Yet, without thinning they will significantly affect current and future multiresource diversity and multiresource yields of recreation, wildlife, water, forage, and timber.

A research need is to evaluate how the ecology and productivity of the ponderosa pine ecotype differs across major soil types in the region. A new timber model that can accurately project growth and potential product yields across soils types, precipitation regimes, and landforms would be valuable.

A more progressive look should be taken at the needs and interests of the southwest constituency, and assess how improved silvicultural management can

best respond to these needs and interests. That is, what should be the correct mix of wilderness, old growth, and commercial timber base, and what should be the silvicultural management regime for the commercial base. For example, in the commercial timber base, what general basal area management goals should be sought for obtaining best commodity and amenity benefit. We must be cautious in our assessments, especially as regards future needs for resources such as wildlife, timber, and nonconsumptive water uses. Population growth and changes and economic development over time may significantly alter the demand function on these resources.

Improve Integrated Resource Management

This goal captures critically needed applied research in integrated multiresource forest management. It is an area where the research community has generally failed the forest manager. It is also the area where intense conflict will occur over the next several decades unless the research community can provide more and better information regarding appropriate management policies and good definition of the multiresource impacts of management.

Every day, the forest manager must make decisions, and in general, the decisions are acceptable. However, they are sometimes impaired by the lack of good science. The manager faced with this dilemma tries to make the decision so as to minimize the risk of negative impact.

However, the manager does not have the option of not acting. Hunters want to hunt, recreationists want to camp, forest industry needs wood, and wildlife need forage. The management decision process will therefore continue, in spite of the lack of adequate information and expertise for a perfect management decision.

Managers want to improve the decision process. They therefore try to use the best science available. The real dilemma is that science has not kept pace with the overwhelming issues in multiresource forest management.

At least two major research efforts are critically needed in the next decade to address these problems.

1. Policy research on who gets to decide the types of multiresource uses we manage for, and how we implement the decision process.

2. Procedures for determining best multiresource management practice

There are many questions in the policy research arena, but two seem critical.

1. Where should the authority best reside for determining the proper multiresource use for public lands in the southwest region? The U.S. general public, the southwest general public, U.S. Congress, the states, the courts, professional foresters, or all of the above? If all of the above, then which groups have the right to decide what part of the issue? How should the authorities be distributed?
2. If we can approach a solution to the first question, that is, who gets to decide, then we should resolve a second question: what is the best implementation process for accomplishing it. For example, one necessary step to implementing multiresource management would be to determine how much timber should be harvested. If each state were given the authority to decide the annual harvest level in the state, how should they arrive at the decision? Should it be done by passing a law? Popular vote? Congressional or executive mandate? Binding arbitration?

If we can assume that we can determine who has the right to decide the mix of uses, and how they get it done, then somehow, we must determine the best multiresource management practice for attaining the goal. Anyone who is now in this science area knows the practice must respond to three critical needs.

1. The research and management direction must incorporate understanding of many multiresources, and their individual and joint productivities over time and space. The research process must merge the talents of researchers and managers from the concept phase, and research must be carried out on large areas such as watersheds, not on individual plots.
2. In the near term the management direction must be definable with differing resolutions of data input, and it must accommodate planning needs at a forest level (one million+ acres) and implementation needs at a project level (1,000 - 5,000 acres). Further the rationale and process

in the various approaches must be congruent in their direction.

3. Analytic systems must be a central methodology in the process to assure timely, reproducible results that are cost effective, rational, consistent, and understandable.

Assure Biodiversity and Ecological Stability

What the general public, and all forest constituency would like in the Southwest and other regions is maximum biological diversity and a stable ecology, while maintaining support to important social and economic interests at satisfactory levels. For example, there is a need for the Tonto National Forest to serve as many social and economic needs or desires as possible, while at the same time maintaining its biophysical diversity, and physical and ecology base. Is this being accomplished? Considering the demand level, yes, but there is always the need to do a better job.

In the southwest ponderosa pine type, the research goals for biological diversity need better definition. This relates to the fact that biological diversity today across the ponderosa pine ecosystem is an artifact of man's intervention. This is primarily due to fire management, but also relates to long term timber, recreation, range, and water management activities. That is, it may be difficult to define, much less strive for a biological diversity that existed before man's intervention, since today we have almost 100 years of fire management. The definition then, will probably ascribe more to a managed state.

Second, the southwest forest based constituency may or may not want the biodiversity of the original unmanaged forest or the current managed forest. This needs to be determined.

Whatever forest biodiversity is desired, it will need better definition. This will require considerable ecological research to contrast biodiversities of various managed forest states across space and time streams. That is, although biodiversity in an overmature old growth forest is somewhat steady state, managed forest biodiversity constantly changes over time. Investigations of differing silvicultural systems and their time stream biodiversities are required to answer the above question.

Understanding the stability of the ecology and physical reserve base also requires more research effort, especially as regards cumulative effects over time. Overall, we do not seem to have a severe problem. That is, we are a class one airshed, we have limited toxic waste dumping, our water is relatively clean, and tree harvest, mining, and agriculture are well managed. That is, in contrast to New Jersey and southern California our ecology is probably more stable and receiving less impact.

However, research problems are surfacing at an alarming rate, and need to be addressed. Research in the following areas, in particular, need immediate attention.

- Air quality, especially as regards visual quality, needs more research. Prescribed fires, dust, and stack emissions need more evaluation to determine their combined impacts on our airshed over time.
- Water quality is an issue that will continue to create increased problems as regards sediment loads and dissolved toxins.
- Riparian ecologies are a critical issue throughout the state due to vacillation of instream flows and conflicts over multiple use (fisheries, grazing, tree harvest, nonconsumptive and consumptive water management).

LITERATURE CITED

- Baker, Malchus B., Jr. 1986. Effects of ponderosa pine treatments on water yield in Arizona. Water Resources Research. Vol. 22, No. 1, pages 67-73.
- Balda, Russell P., and Nancy Masters. 1980. Avian communities in the pinyon-juniper woodland: A descriptive analysis. p. 146-167. In Workshop proceedings: Management of western forests and grasslands for nongame birds. USDA Forest Service General Technical Report INT-86, 535 p. Intermountain Forest and Range Experiment Station, Ogden, Utah.
- Brown, Harry E., Malchus B. Baker, Jr., James J. Rogers, et al. 1974. Opportunities for increasing water yields and other multiple use values on ponderosa pine forest lands. USDA Forest Service Research Paper RM-129, 36 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.
- Clary, Warren P. 1975. Range management and its ecological basis in the ponderosa pine type of Arizona. The status of our knowledge. USDA Forest Service Research Paper RM-158, 35 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.
- Covington, W.W., and S.S. Sackett. 1984. The effect of a prescribed burn in southwestern ponderosa pine on organic matter and nutrients in woody debris and forest floor. Forest Science 30:103-162.
- Cunningham, James B., Russell P. Balda, and William S. Gaud. 1980. Selection and use of snags by secondary cavity-nesting birds of the ponderosa pine forest. USDA Forest Service Research Paper RM-222, 15 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.
- Daniel, Terry C., and Ron S. Boster. 1976. Measuring landscape esthetics: The scenic beauty estimation method. USDA Forest Service Research Paper RM-167, 66 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.
- Ffolliott, Peter F., and E.A. Hansen. 1968. Observations of snowpack accumulation, melt, and runoff on a small Arizona watershed. USDA Forest Service Research Note RM-124, 7 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.
- Garrett, L.D. 1985. Understanding multiresource options on Arizona's National Forest System Lands. In Proceedings of Arizona Water Resources Committee Annual Meeting. Arizona Water Resources Committee, Phoenix, Arizona.
- Larson, Frederic R. 1975. Simulating growth and management of ponderosa pine stands. 118 p. Ph.D. dissertation, Colorado State University, Fort Collins.
- Little, Elbert L., Jr. 1979. Checklist of United States trees (native and

naturalized). Agric. Handbook 541. Washington, D.C.: U.S. Department of Agriculture. 375 p.

Minor, Charles O. 1964. Site-index curves for young-growth ponderosa pine in northern Arizona. USDA Forest Service Research Note RM-37, 8 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Patton, David R. 1978. Run Wild: A storage and retrieval system for wildlife habitat information. USDA Forest Service General Technical Report RM-51, 8 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Rogers, James J., Joseph M. Prosser, Lawrence D. Garrett, and Michael G. Ryan. 1984. ECOSIM: A system for projecting multiresource outputs under alternative forest management regimes. Administrative Report, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Sackett, Stephen S. 1979. Natural fuel loadings in ponderosa pine and mixed conifer forests of the Southwest. USDA Forest Service

Research Paper RM-213, 10 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Sackett, Stephen S. 1980. Reducing natural ponderosa pine fuels using prescribed fire: Two case studies. USDA Forest Service Research Note RM-392, 6 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Tecle, Aregai, Martin M. Fogel, and Lucien Duckstein. 1988. Multicriterion analysis of forest watershed management alternatives. Water Resources Bulletin, 24(6):1169-1178.

USDA Forest Service, National Association of Professional Schools and Colleges, and USDA Cooperative State Research Service. 1989b. Forests for America's Future: A Research Program for the 1990's. USDA Forest Service, Washington, D.C.

USDA Forest Service. 1989a. Draft 1990 RPA Program. USDA Forest Service, Washington, D.C.

Areal Growth and Distribution of Ponderosa Pine Forests: Moderator's Comments

**Richard Bassett
USDA Forest Service**

The modern distribution of ponderosa pine consists of large, discontinuous populations established over a wide area of the western United States and southwestern Canada. Fossil records of the species indicate distributional changes have occurred during the last 10,000 years. The establishment of large populations within the arid Southwest may be a function of the development of the summer precipitation maximum during the monsoon.

Throughout its range, ponderosa pine is an important species, not only for its commercial timber value, but the forests are also used for recreation and to provide forage for wildlife and domestic livestock, and it is also cover for wildlife. Logging and grazing practices since the 1850s, as well as fire control, have altered the forest structure and species composition. Timber harvest practices have resulted in an uneven-aged

structure with dense smaller trees and a low density of snags. Livestock grazing has contributed to changes in vegetation structure, species composition, and fire response. Fire control has resulted in the increase of white fir and juniper in pine forests, especially in California.

Little thinning was done in Southwestern ponderosa pine forests until the 1950s. A series of thinning guides have been developed and used since that time.

Long term growth records are becoming increasingly important to understanding tree and stand growth trends under changing environmental or climatological conditions. Analysis of dendrochronological data have undergone recent statistical improvement with the incorporation of extensive computer editing and Kalman filter algorithms.

Development of the Southwestern Ponderosa Pine Forests: What Do We Really Know?¹

R. Scott Anderson²

Abstract.--The modern distribution of ponderosa pine (*Pinus ponderosa*) consists of large, discontinuous populations within the western United States and southwestern Canada. However, the former distribution and abundance of the species over the last 14,000 years is not well known. The Southwestern and Rocky Mountain variety exhibited a latitude and altitudinal expansion after ca. 10,600 yr BP, while present evidence is insufficient to confirm other than a predominantly altitudinal expansion of the tree in the Sierra Nevada of California.

INTRODUCTION

Ponderosa pine (*Pinus ponderosa* Laws.) is one of the most widely distributed trees within montane western North America, occurring from northern Mexico into southern British Columbia (fig. 1; Little 1971). The species is separated geographically and genetically into at least two distinct varieties (Critchfield 1984). *Pinus ponderosa* var. *ponderosa* occurs mainly in California and the Pacific Northwest, while *P. p.* var. *scopulorum* occurs within the Rocky Mountain region, Utah, New Mexico and Arizona. These varieties are sympatric only in central Montana. A third variety, *P. p.* var. *arizonica*, is described from southeastern Arizona (Kearney and Peebles 1951), but is largely a Mexican form.

Although an important tree from the standpoint of lumber production and recreational value, with a large literature on the silviculture of the species, little is known regarding the fossil history of ponderosa pine, or the history of the vegetation type in general. How long have these forests been established? What was the glacial-age distribution of the species? What was the postglacial

pattern of migration into the Southwest since the last glacial age? What can be determined regarding the glacial refugium of the tree? This paper reviews the literature on the subject, compiled since the brief discussion by Critchfield (1984), and concentrates on the Sierra Nevada of California and at sites within Arizona and surrounding states. I also present new data for the two areas, suggesting minimum ages for the establishment of the tree within its modern range in California, and of the ponderosa pine forest type on the Mogollon Rim, Arizona.

Modern Occurrence in Arizona and California

In the Sierra Nevada of California, *Pinus ponderosa* var. *ponderosa* occurs on relatively xeric sites within the Sierra Montane forest. In the northern part of the range, it grows in a belt from 300 - 1800 m (980 - 5900 ft) elevation, rising to 1200 - 2100 m (3900 - 6900 ft) as far south as Sequoia National Park (Rundel et al. 1988). Modern associates include white fir (*Abies concolor*), douglas-fir (*Pseudotsuga menziesii*), California black oak (*Quercus kelloggii*) and incense-cedar (*Calocedrus decurrens*), among others. Unlike areas of the southern Colorado Plateau in Arizona, ponderosa pine rarely occurs in pure stands in California. Details of the history of the Sierra Montane forest type are found elsewhere (Anderson 1987, 1990).

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²R. Scott Anderson is Assistant Research Professor in the Quaternary Studies Program and Bilby Research Center, Northern Arizona University, Flagstaff, Ariz.

The largest continuous stand of the species is found within northern Arizona, along the southern margin of the Colorado Plateau, an unbroken band of trees ca. 40 to 65 km wide and

nearly 480 km long (Cooper 1960). This dominant constituent of the Sierra Montane Conifer Forest (Brown and Lowe 1977) occupies much of the mountain and plateau country above ca. 1980 m (6500 ft). Above ca. 2590 m (8500 ft), ponderosa pine is largely replaced by douglas-fir, white fir and other species.

Within northern and central Arizona, the typical form *P. ponderosa* var. *scopulorum* Engelm. is most common (Kearney and Peebles 1951). This form differs from other populations within the Rocky Mountains in having three needles per fascicle instead of two (Haller 1965). However, in the mountains of several southern Arizona counties--Graham, Cochise, Santa Cruz and Pima--the common form is var. *arizonica* (Engelm.) Shaw, which has five needles per fascicle. In certain mountain ranges, such as the Santa Catalina Mountains of Pima County, both forms are reported.³

Determining Late Quaternary Plant Distributions

Records of plant biogeography and vegetation change during the late Quaternary are obtained in two ways. Pollen and plant macrofossils are often found in stratigraphic deposits, usually lake and alluvial sediments laid down within a basin or along a stream course. Many of our longest vegetation records

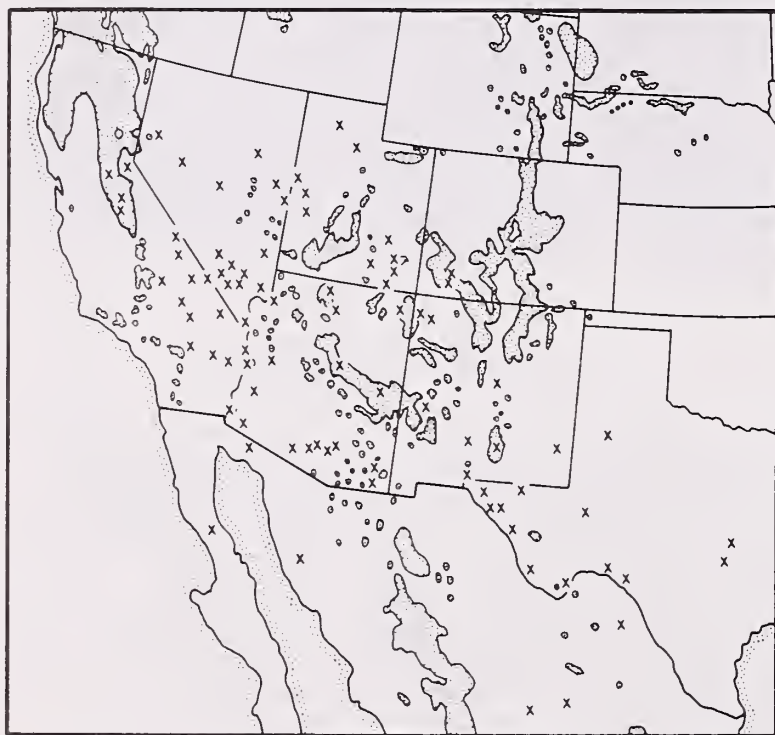


Figure 1.--Modern distribution of ponderosa pine in the Southwest and California (stippled after Little 1971) with the distribution of fossil packrat and pollen sites, (x-mark; after Spaulding et al. 1983, Van Devender et al. 1987, Anderson unpublished).

³Van Devender, T.R. 1989. Personal conversation. Arizona-Sonora Desert Museum, Tucson, Ariz.

are deduced from the analysis of stratigraphic deposits. In addition, the deposits generally represent uninterrupted sedimentation, allowing the paleoecologist to "view" vegetation change at short intervals. One problem is that continuous deposits, particularly lacustrine deposits, are uncommon in much of the arid Southwest. In Arizona, natural lakes are confined to areas along the Mogollon Rim, the Kaibab Plateau, the White Mountains and other high elevation areas of the region. Playa lakes, such as Willcox Playa in southeastern Arizona (Pluvial Lake Cochise during the last glacial episode), occupy some lowland basins. Lakes from mid-elevations (i.e., Montezuma Well, Pecks Lake in Yavapai County, Arizona), are rare and occur only under specialized conditions. Conditions within the Sierra Nevada are much the same, with sedimentary basins confined largely to ca. 1980 m (6500 ft) and above.

Packrat (*Neotoma* sp.) midden deposits are abundant throughout the lower elevation deserts, and also preserve pollen and plant remains in excellent condition. Packrats are prolific collectors of plant materials within 30 - 50 m of their nests (Finley 1958; Bleich and Schwartz 1975). These deposits are generally confined to rocky shelters and scarps, and are rarely preserved in the valley bottoms or exposed locations. In addition, middens are not deposited continuously; depositional events (formation of middens) may be separated by hundreds to thousands of years. However, most of the vegetational history of the lowland regions of the area has been deduced from the analysis of these middens (Van Devender et al. 1987). More than 1,100 packrat middens have been analyzed and radiocarbon dated (Webb 1985).

With the analysis of fossil assemblages contained within stratigraphic deposits and packrat middens, placed into a temporal context with radiocarbon dating, the picture of vegetation change within the desert Southwest has come into greater focus. However, large gaps within this story still occur. One of these stories is that of ponderosa pine.

THE LATE QUATERNARY FOSSIL RECORD OF PONDEROSA PINE

Though today ponderosa pine is perhaps the most conspicuous conifer at mid- to higher elevations within the region, the fossil record of the tree is largely unknown. Axelrod (1988) recorded *Pinus* cf. *ponderosa* remains of Miocene age from west-central Nevada, with additional locations of Pliocene age. The earliest Quaternary record, estimated at >100,000 years old, is that of Baker (1986), who found remains in Sangamonian-age sediments within Yellowstone National Park, Wyoming; the tree presently does not grow within that park. Of the nearly 75 packrat midden and ca. 20 stratigraphic deposits within the desert Southwest and Sierra Nevada of

California (fig. 1; Spaulding et al. 1983; Van Devender et al. 1987; Anderson, unpublished), only a handful contain definitive presence of ponderosa pine during the latest glacial episode (late Wisconsin).

The oldest of these sites occurs in California where needles of the tree were found in packrat middens dating 12,500 to >45,000 yr BP (fig. 2; Kings Canyon, 980 - 1280 m; 3215 - 4200 ft; Cole 1983), occurring several hundred meters below its modern limit. Ponderosa pine grew at Log Meadow (2086 m, 6840 ft; Sequoia National Park) by ca. 11,150 yr BP (Anderson, unpublished), and near the Meadow of Honor (1875 m, 6150 ft; Kings Canyon National Park) by ca. 10,125 yr BP (Anderson, unpublished). Further north in Yosemite National Park, remains as old as ca. 12,200 yr BP were recovered from sediments of Swamp Lake (Smith 1989; Anderson, unpublished). Since the tree grows near the lake today (1554 m; 5100 ft), a minimum date is provided for the arrival of the species within its modern elevational range. In all cases except Swamp Lake, ponderosa pine was found in association with remains of other tree species with which it grows today. Thus, plant associations within the modern Sierra Montane forests of California had begun to coalesce by the end of the late Wisconsin (Anderson 1987, 1990).

Outside of California, late Wisconsin records of the tree are equally rare (fig. 2). In the San Andres Mountains of New Mexico (1705 m; 5590 ft) today a transition between desert grassland and pinyon - juniper (*Pinus edulis* - *Juniperus monosperma*) woodland,

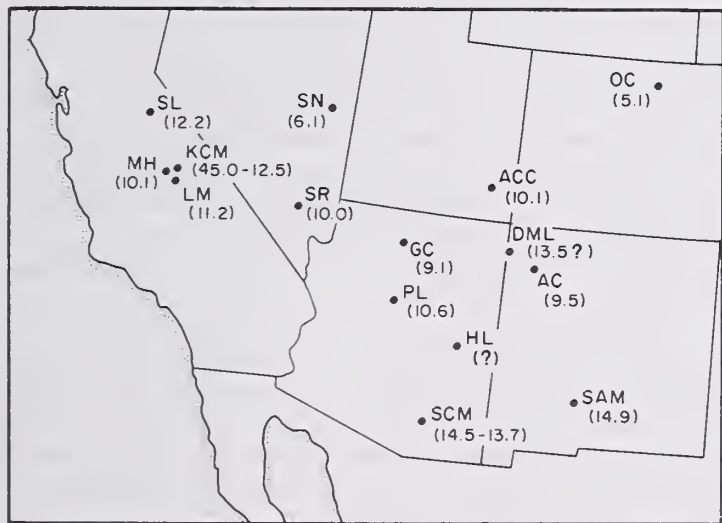


Figure 2.--Fossil distribution (first occurrence) of ponderosa pine with radiocarbon ages (yr BP x 1000); SN = Snake Range; SR = Sheep Range; OC = Owl Canyon; ACC = Allen Canyon Cave; GC = Grand Canyon; DML = Dead Man Lake; AC = Atlatl Cave; PL = Potato Lake; HL = Hay Lake; SCM = Santa Catalina Mts.; SAM = San Andres Mts.; SL = Swamp Lake; MH = Meadow of Honor; KLM = Kings Canyon middens; LM = Log Meadow.

Van Devender (1990a) reported ponderosa pine needles associated with douglas-fir, Colorado blue spruce (*Picea pungens*) and one-seeded juniper (*Juniperus monosperma*) in a single midden dating ca. 14,920 yr BP. The fossil needles are of the "scopulorum" type. Pollen identified as ponderosa pine was found in sediments of Deadman Lake (elevation 2780 m, 9120 ft); Chuska Mountains, New Mexico), estimated at ca. 13,500 yr BP (Wright et al. 1973). Ponderosa pine grows around the lake today. No plant macrofossils were found in the sediments to confirm local presence; identification of the pollen to species was based on pollen morphological characteristics alone (Hansen and Cushing 1973).

In the Santa Catalina Mountains near Tucson, southern Arizona, ponderosa pine needles, as well as remains of Arizona cypress (*Cupressus arizonica*) and douglas-fir, were found in packrat middens from modern desert grassland (elevation 1555 m; 5100 ft), dating ca. 14,450 to 13,670 yr BP (Thompson and Van Devender 1982; Van Devender 1990b). These midden records do not reflect significant changes in the plant distributions, though, as the tree can be found in more mesic canyon sites at nearly the same elevation today. As at the San Andres site, the remains are of the "scopulorum" type, not the "arizonica" variety most common in the range today.⁴

Jacobs (1983) utilized palynological techniques to identify the presence of diploxylon pine-type (includes both ponderosa and lodgepole pine, *P. contorta*) pollen in sediments of Hay Lake, Arizona, (elevation 2780 m; 9210 ft), deposited by ca. 29,000 years ago. She suggested a more widespread occurrence at lower elevations of either or both species since near alpine conditions occurred around the lake at that time. No plant macrofossils were found to confirm presence, however; only ponderosa pine grows near the lake today.

In northern Arizona, diploxylon-type pine pollen may have been present in sediments of Crane Lake (elevation 2590 m; 8500 ft) as early as ca. 11,000 yr BP (Shafer 1989). Irregularities in radiocarbon dating of the profile suggest caution in interpretation, however. Betancourt (1984) recorded ponderosa pine needles at Allen Canyon Cave, southeastern Utah (elevation 2195 m; 7200 ft), in a midden dating ca. 10,140 yr BP. Nearby Fishmouth Cave (1585 m; 5200 ft) did not have ponderosa pine remains, although the record stretched back to ca. 12,770 yr BP.

At other Southwestern sites, however, ponderosa pine did not become abundant until somewhat later in the early Holocene. These

⁴Van Devender, T.R. 1989. Personal conversation. Arizona-Sonora Desert Museum, Tucson, Ariz.

include the Sheep Range in southern Nevada (2400 m; 7875 ft; by 10,060 yr BP; Van Devender and Spaulding 1979), Atlatl Cave, Chaco Canyon, New Mexico (1910 m; 6270 ft; by 9500 yr BP; Betancourt and Van Devender 1983) and the eastern Grand Canyon, Arizona (1770 - 1900 m, 5800 - 6230 ft; by 9100 yr BP; Cole 1982). Changing climate no longer favored ponderosa pine at the Grand Canyon sites after ca. 8430 yr BP, while the species was extirpated locally near Atlatl Cave by ca. 2400 yr BP.

Somewhat further to the north, the species grow in the Snake Range of eastern Nevada by 6120 yr BP (2040 m; 6700 ft; Thompson 1984). It occurred at Owl Canyon near Ft. Collins, Colorado, by 5090 yr BP (1860 m; 6100 ft; Betancourt 1987) and in southeastern Wyoming by 4060 yr BP (Wells 1970).

These observations suggest two hypotheses. First, ponderosa pine was probably absent or extremely rare on the Colorado Plateau and northerly locations during the latest Wisconsin (ca. 11,000 - 14,000 years ago), and that the extensive forests of today all date subsequent to that time period. Second, the species exhibits a different biogeographic history in the Sierra Nevada of California than on the Colorado Plateau and in southern Arizona and New Mexico. The first observation will be discussed in light of a continuous sediment record from a small lake near Flagstaff, Arizona. The second will be discussed subsequently.

THE RECORD FROM POTATO LAKE, ARIZONA

Potato Lake is a small solution feature within the Permian Coconino Sandstone, Coconino County, Arizona. At 2222 m (7290 ft) elevation, it is near the average elevation of the Mogollon Rim. Thus, the record of vegetation history of the basin should be typical of the southern margin of the Colorado Plateau in general. Sediments from this site were originally studied by Whiteside (1965), who identified the pollen and microalgae assemblages deposited there over the last approximately 15,000 years. With these new data (Anderson et al. 1989), the record is extended back to ca. 35,000 yr BP, into the last interstadial (middle Wisconsin). This is important because the middle Wisconsin is thought to have been a warm interval. I wondered if the mid-Wisconsin interval was warm and/or wet enough to support ponderosa pine forests as today. These new data include not only pollen but plant macrofossil remains as well, establishing local presence of several western conifers.

During the mid-Wisconsin interval (pollen Zone I; ca. 35,000 to 23,500 yr BP), dominant pollen types are spruce (*Picea*, needles of *P. englemannii*, fir (needles of *Abies concolor*, large haploxylon pine (*Pinus*), juniper, oak, sagebrush (*Artemisia*), other Compositae and

grasses (Gramineae) (Anderson et al. 1989; fig. 3). Macrofossils of douglas-fir are also found. Diploxylon pine pollen, represented by either ponderosa or lodgepole pine, is conspicuously absent.

During Zone II, the late Wisconsin cold interval dated here ca. 23,500 - 10,400 yr BP, dominant pollen types are spruce, fir, large haploxylon pine, sagebrush, pinyon pine and Chenopodiaceae-Amaranthus. Only macrofossils of Englemann spruce are found.

However, by 10,400 yr BP (pollen Zone III), pollen of boreal conifers (spruce, fir, haploxylon pine), as well as sagebrush, is very much diminished. Instead, dominant pollen types are diploxylon pine (represented by the first occurrence of ponderosa pine needle fragments by ca. 10,600 yr BP), oak, grasses and other composites. Higher percentages of aquatic and wetland plants, such as *Potamogeton* (pondweed), *Typha latifolia* (cattail), Cyperaceae (sedge) (Anderson, unpublished; Whiteside 1965) indicate much lowered lake levels. Sediment accumulation rates drop considerably and a hiatus of deposition may be apparent for the early Holocene, i.e., the lake may have dried completely.

This three part zonation of vegetation for the Mogollon Rim area over the last 35,000 years can be summarized as follows: An open Englemann spruce - white fir - douglas-fir forest, with an understory of sagebrush, grasses and composites, existed around Potato Lake during the mid-Wisconsin interstadial. Although the record of wetland and aquatic plants indicates relatively high lake levels (relatively wet conditions), the climate was neither warm enough nor perhaps wet enough during the summer to allow the establishment of ponderosa pine on or near the Mogollon Rim at this elevation. During the late-Wisconsin cold period (ca. 23,500 - 10,400 year BP), colder climatic conditions intensified, allowing Englemann spruce to predominate near the lake. I interpret this assemblage as representing a closed spruce forest, with additional mixed conifers occurring in very low abundance. A ponderosa pine forest became established sometime after 10,600 yr BP, with the immigration of ponderosa pine into the watershed of Potato Lake. This forest may have been somewhat different than today, with perhaps more oak and greater forest openings occupied by non-arboreal plants such as grasses and composites. This also establishes the time of origination of the modern biseasonal precipitation regime, the summer precipitation maximum called the "Arizona Monsoon" (Sellers and Hill 1974).

LATE QUATERNARY BIOGEOGRAPHY OF PONDEROSA PINE

Although the fossil record of ponderosa pine through time is only sporadically docu-

POTATO LAKE, COCONINO COUNTY, ARIZONA

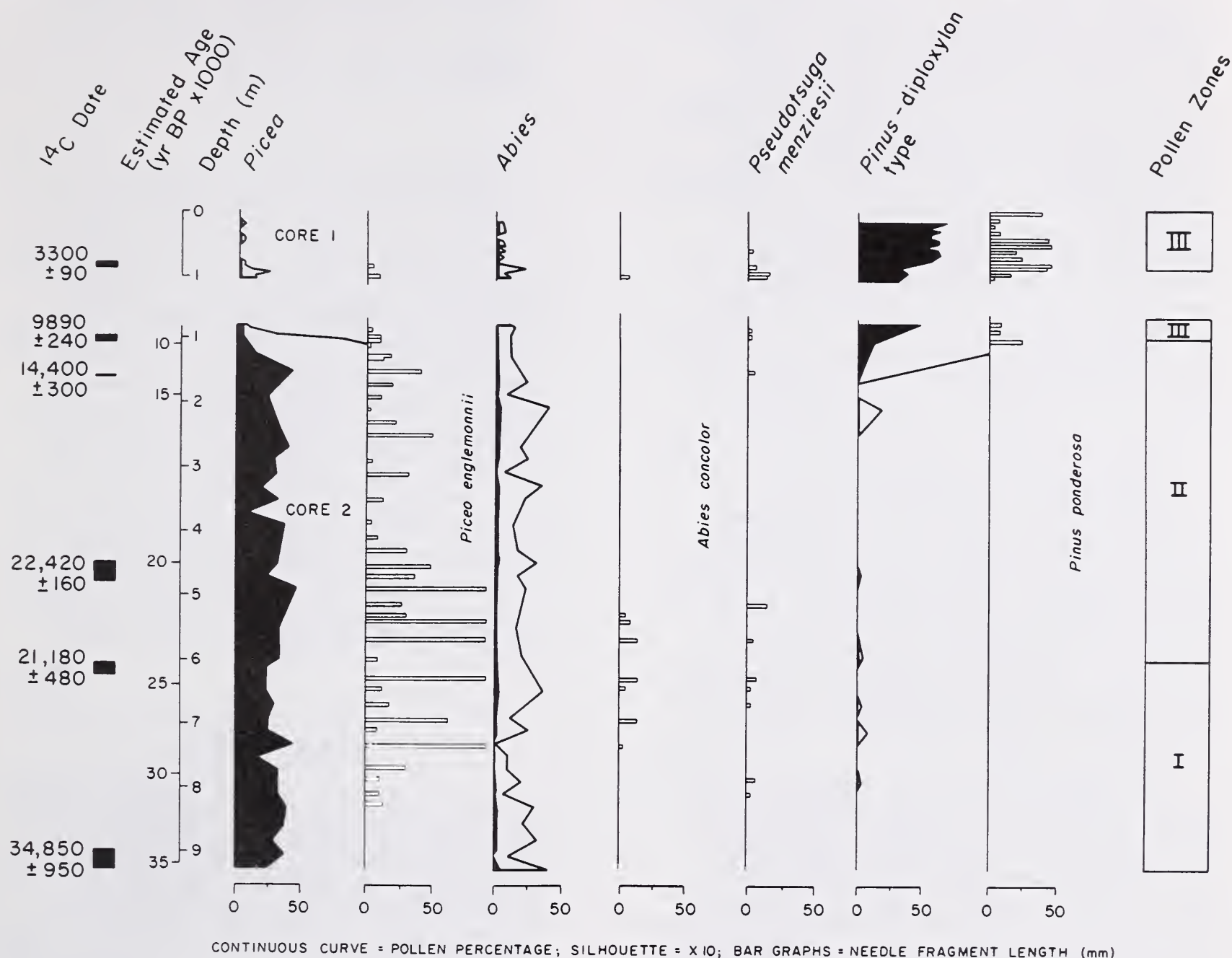


Figure 3.--Pollen and plant macrofossils of selected conifers from the Potato Lake, Arizona, sediment cores. Estimated age scale as in Anderson et al. (1989).

mented in the Southwest and California, it is apparent that the late Quaternary history of the species has been different between the two areas. For California, ponderosa pine has been found largely within the same geographic area for at least the last 45,000 years (figs. 1 and 2). However, during the mid- and late-Wisconsin, the tree grew at considerably lower elevations (980 - 1280 m) than it presently does. The tree became established within its present elevational range ca. 11,000-12,000 years ago. Apparently the gentle western slopes of the northwest - southeast trending Sierra Nevada range allowed for simple downslope migration in response to climatic cooling during the Wisconsin (Tioga) glacial episode and up-slope migration during the present interglacial.

Data are not sufficient to evaluate the possibility of southward migration also during the last glaciation.

The situation within the American Southwest suggests that ponderosa pine probably underwent a more radical southward migration there during the last glacial episode. The oldest records are found in middens from southeastern Arizona and southcentral New Mexico. All other records except Deadman Lake and Crane Lake suggest establishment of ponderosa pine on the Colorado Plateau no earlier than 10,600 yr BP. The estimated age from Deadman Lake (fig. 3; Wright et al. 1973) is based on interpolation between a Wisconsin-age date and the present, and may be

in error by several thousand years. Dating problems also occur for Crane Lake (Shafer 1989; see above). Neither of these ages are supported by direct occurrence of plant remains themselves, only by pollen data, while the other ages are based on occurrence of plant macrofossils alone or with pollen of ponderosa pine. Indirect evidence also comes from absence of ponderosa pine in virtually all of the packrat midden series from elevations lower than its modern range for the Wisconsin (Van Devender et al. 1987). It almost certainly did not retreat to lower elevations and expand on valley bottoms within the region (Betancourt and Van Devender 1983; Betancourt and Davis 1984), as originally suggested by Martin and Mehringer (1965) and Wright et al. (1973). It is possible that it survived in isolated, mesic habitats, an idea proposed for pinyon pine by Cinnamon and Hevly (1988). However, no direct evidence has been found to support this hypothesis.

Just as the actual Wisconsin refuge remains a mystery, so does the immigration of *P. ponderosa* var. *arizonica*. This predominantly five-needled pine is the most common variety within the Santa Catalina Mountains of southern Arizona today. However, both the late Wisconsin middens from that location and the San Andres Mountains of New Mexico contain exclusively the three-needled variety, *P. p.* var. *scopulorum*⁵. Whether this suggests the development of var. *arizonica* during the Holocene, or is a result of a paucity of samples cannot be answered without more data.

The modern distribution of ponderosa pine within the Southwest has often been linked to the areas receiving significant summer precipitation (Betancourt 1984; Shafer 1989). This "Arizona Monsoon" (Sellers and Hill 1974) impacts an area roughly bounded on the east by the Colorado River and Colorado Plateau, on the north by southern Wyoming and to the east by the Colorado Front Range (Mitchell 1976). Climatic models (Kutzback and Guetter 1986; COHMAP 1988) and empirical data (Spaulding et al. 1983; Spaulding and Graumlich 1986) suggest a greatly weakened monsoon during the glacial maximum over that of today. An intensified monsoon during the latest Wisconsin and early Holocene, along with climatic warming, undoubtedly created the opportunity for the expansion of ponderosa pine in that region.

This is not the case for ponderosa pine in California, which does not experience significant summer precipitation today (Major 1988), and was apparently drier during the early Holocene (Davis et al. 1985; Anderson 1987, 1990). Clearly summer precipitation has not been a limiting factor here. Perhaps winter precipitation has been sufficient, enabling soil

moisture levels to remain high enough for ponderosa pine establishment. Alternatively, genetic differences between the California and Southwestern varieties of ponderosa pine (see Critchfield 1984) may account for these responses to changing climate.

CONCLUSIONS

The distribution of ponderosa pine in the Southwest was strikingly different during the last glacial episode. The tree was largely absent from much of its modern range during that time. Although no direct fossil evidence has been found, it may have survived south of the Santa Catalina Mountains of Arizona, and expanded northward coincident with the onset of climatic warming and intensification of the summer monsoon. Alternatively, ponderosa pine survived in very isolated, mesic microhabitats within or near its modern range and from which we have no substantiated fossil record. Somewhat different conditions prevailed in the Sierra Nevada of California, where remains of tree are found dating back to 45,000 years ago. Thus, the eastern populations of the species exhibited a largely latitudinal (and undoubtedly altitudinal) expansion while present evidence is insufficient to confirm other than a predominantly altitudinal expansion of the tree in California.

ACKNOWLEDGEMENTS

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LITERATURE CITED

- Anderson, R.S. 1987. Late Quaternary environments of the Sierra Nevada, California. Ph.D. Dissertation, University of Arizona, Tucson. 290 p
- Anderson, R.S. 1990. Holocene forest development and paleoclimates within the central Sierra Nevada, California. *Journal of Ecology*.
- Anderson, R.S., S. Smith, D. Rothstein, L. Murray, E. Hadly, C. Force and S. Diveley-White. 1989. The mid- and late-Wisconsin pollen stratigraphy of Potato Lake, Coconino County, Arizona. *Current Research in the Pleistocene* 6:51-54.
- Axelrod, D.I. 1988. Outline history of California vegetation. In *Terrestrial Vegetation of California*. Edited by M.G. Barbour and J. Major. California Native Plant Society, Special Publication 9. pp. 139-194.

⁵Van Devender, T.R. 1989. Personal conversation. Arizona-Sonora Desert Museum, Tucson, Ariz.

- Baker, R.G. 1986. Sangamonian(?) and Wisconsinan paleoenvironments in Yellowstone National Park. Geological Society of America Bulletin 97:717-736.
- Betancourt, J.L. 1984. Late Quaternary plant zonation and climate in southeastern Utah. Great Basin Naturalist 44:1-35.
- Betancourt, J.L. 1987. Paleoecology of pinyon-juniper woodlands: Summary. In Proceedings, Pinyon-Juniper Conference Compiled by R.L. Everett. USDA Forest Service Gen. Tech. Rpt. INT-215, pp. 129-139.
- Betancourt, J.L. and O.K. Davis. 1984. Packrat middens from Canyon de Chelly, northeastern Arizona: paleoecological and archaeological implications. Quaternary Research 21:56-64.
- Betancourt, J.L. and T.R. Van Devender. 1983. Fossil packrat middens from Chaco Canyon, New Mexico: cultural and ecological significance. In Chaco Canyon Country. Edited by S.G. Wells, D. Love, and T.W. Gardner. American Geomorphological Field Group, 1983 Field Trip Guidebook. pp. 207-217.
- Bleich, V.C. and O.A. Schwartz. 1975. Observation on the home range of the desert woodrat, *Neotoma lepida intermedia*. Journal of Mammalogy 56:518-519.
- Brown, D.E. and C.H. Lowe. 1977. Biotic communities of the Southwest (Map). USDA Forest Service, General Technical Report RM-41.
- Cinnamon, S.K. and R.H. Hevly. 1988. Late Wisconsin macroscopic remains of pinyon pine on the northern Colorado Plateau, Arizona. Current Research in the Pleistocene 5:47-48.
- COHMAP. 1988. Climatic changes of the last 18,000 years: observations and model simulations. Science 241:1043-1052.
- Cole, K.L. 1982. Late Quaternary zonation of vegetation in the eastern Grand Canyon. Science 217:1142-1145.
- Cole, K.L. 1983. Late Pleistocene vegetational changes of Kings Canyon, Sierra Nevada, California. Quaternary Research 19:117-129.
- Cooper, C.F. 1960. Changes in vegetation, structure, and growth of southwestern pine forests since white settlement. Ecological Monographs 30:129-164.
- Critchfield, W.B. 1984. Crossability and relationships of Washoe pine. Madrono 31:144-170.
- Davis, O.K., R.S. Anderson, P.F. Fall, R.S. Thompson, and M.K. O'Rourke. 1985. Palynological evidence of Early Holocene aridity in the southern Sierra Nevada of California. Quaternary Research 24:322-332.
- Finley, R.B. 1958. The woodrats of Colorado, distribution and ecology. University of Kansas Publications, Museum of Natural History 10:213-552.
- Haller, J.R. 1965. The role of 2-needle fascicles in the adaptation and evolution of ponderosa pine. Brittonia 17:354-382.
- Hansen, B.S. and E.J. Cushing. 1973. Identification of pine pollen of Quaternary age from the Chuska Mountains, New Mexico. Geological Society of America Bulletin 84:1181-1200.
- Jacobs, B.F. 1983. Past vegetation and climate of the Mogollon Rim area, Arizona. Ph.D. Dissertation, University of Arizona, Tucson. 166 p.
- Kearney, T.H. and R.H. Peebles. 1951. Arizona flora. 1032 p. University of California Press, Berkeley, CA.
- Kutzback, J.E. and P.J. Guetter. 1986. The influence of changing orbital parameters and surface boundary conditions on climate simulations for the past 18,000 years. Journal of the Atmospheric Sciences 43:1726-1759.
- Little, E.L., Jr. 1971. Atlas of U.S. trees. Vol. 1. Conifers and important hardwoods. U.S. Department of Agriculture Miscellaneous Publication 1146, 209 p. Washington, D.C.
- Major, J. 1988. California climate in relation to vegetation. In Terrestrial vegetation of California. Edited by M.G. Barbour and J. Major. California Native Plant Society, Special Publication Number 9. pp. 11-74.
- Martin, P.S. and P.J. Mehringer. 1965. Pleistocene pollen analysis and biogeography of the Southwest. In The Quaternary of the United States. Edited by H.E. Wright, Jr. and D.G. Frey. Princeton University Press, Princeton. pp. 433-451.
- Mitchell, V.L. 1976. The regionalization of climate in the western United States. Journal of Applied Meteorology 15:920-927.
- Rundel, P.W., D.J. Parsons, and D.T. Gordon. 1988. Montane and subalpine vegetation of the Sierra Nevada and Cascade Ranges. In Terrestrial vegetation of California. Edited by M.G. Barbour and J. Major. California Native Plant Society, Special Publication 9. pp. 559-600.
- Sellers, W.D. and R.H. Hill. 1974. Arizona climate 1931-1972, Second Edition. University of Arizona Press, Tucson. 616 p.
- Shafer, D.S. 1989. The timing of Late Quaternary monsoon precipitation maxima in the south west United States. Ph.D. Dissertation, University of Arizona, Tucson. 234 p.
- Smith, S.J. 1989. Pollen and microscopic charcoal analysis of a sediment core from Swamp Lake, Yosemite National Park, California. M.S. Thesis, Northern Arizona University, Flagstaff. 85 p.
- Spaulding, W.G. and L.J. Gruamlich. 1986. The last pluvial climatic episodes in the deserts of southwestern North America. Nature 320:441-444.
- Spaulding, W.G., E.B. Leopold and T.R. Van Devender. 1983. Late Wisconsin paleoecology of the American Southwest. In Late Quaternary environments of the United States. Vol. 1. The Late Pleistocene. Edited by S.C. Porter and H.E. Wright, Jr. University of Minnesota Press, Minneapolis. pp. 259-293.
- Thompson, R.S. 1984. Late Pleistocene and Holocene environments in the Great Basin.

- Ph.D. Dissertation, University of Arizona, Tucson. 256 p.
- Thompson, R.S. and T.R. Van Devender. 1982. Late Pleistocene vegetational records from desert grassland in the Santa Catalina Mountains, Arizona. *American Quaternary Association Abstracts* 7:167.
- Van Devender, T.R. 1990a. Late Quaternary vegetation and climate in the Chihuahuan Desert, United States and Mexico. *In* Packrat middens: late Quaternary environments of the arid west. Edited by J.L. Betancourt, T.R. Van Devender and P.S. Martin. University of Arizona Press, Tucson.
- Van Devender, T.R. 1990b. Late Quaternary vegetation and climate of the Sonoran Desert, United States and Mexico. *In* Packrat middens: late Quaternary environments of the arid west. Edited by J.L. Betancourt, T.R. Van Devender and P.S. Martin. University of Arizona Press, Tucson.
- Van Devender, T.R., R.S. Thompson and J.L. Betancourt. 1987. Vegetation history in the Southwest: the nature and timing of the late Wisconsin-Holocene transition. *In* North America and adjacent oceans during the late deglaciation. Edited by W.F. Ruddiman and H.E. Wright, Jr. Geological Society of America, Boulder. pp. 323-352.
- Van Devender, T.R. and W.G. Spaulding. 1979. Development of vegetation and climate in the southwestern United States. *Science* 6:240-244.
- Webb, R.H. 1985. Spatial and temporal distribution of radiocarbon ages of rodent middens from the Southwestern United States. *Radiocarbon* 28:1-8.
- Wells, P.V. 1970. Postglacial vegetational history of the Great Plains. *Science* 167:1574-1582.
- Wells, P.V. 1983. Paleobiogeography of montane islands in the Great Basin since the last glaciopluvial. *Ecological Monographs* 53:341-382.
- Whiteside, M.C. 1965. Paleoecological studies of Potato Lake and its environs. *Ecology* 46:807-816.
- Wright, H.E., Jr., A.M. Bent, B.S. Hansen and L.J. Maher, Jr. 1973. Present and past vegetation of the Chuska Mountains, northwestern New Mexico. *Geological Society of America Bulletin* 84:1150-1180.

The Development of Thinning Practices in Southwestern Ponderosa Pine¹

Ernest A. Kurmes²

Abstract.--Little thinning was done in the dense sapling stands of ponderosa pine in the southwest until the 1950's due to economic considerations and the influence of USFS researcher G.A. Pearson, who favored only very light crop tree thinning. In the past 35 years a series of thinning guides have been developed which have recommended increasingly heavier, uniform thinnings to promote more rapid diameter growth.

Early reports of the southwestern ponderosa pine forests described open forests with well-spaced trees. This condition was probably due to frequent surface fires. With frequent fires little fuel accumulated, particularly under stands of young trees which were not yet producing large amounts of litter each year, so few trees were killed and those that were usually were the smallest and least desirable. Although the fires did not kill trees uniformly or selectively, some thinning was accomplished.

A major goal of foresters in the southwest after the establishment of the national forests was the prevention of wildfires. We were quite successful in meeting this goal, but along with the benefits of reduced fire losses, the effects of fire thinning disappeared. Natural regeneration occurs at intervals, when the requirements of a good seed crop, a desirable seedbed, and adequate rainfall are all met. In the southwest, the most exceptional conditions for natural regeneration occurred when heavy seed production in the fall of 1918 was followed by a warm, wet spring and summer in 1919. Soil surface conditions were probably also unusually good because of heavy grazing during World War I. As a result, thousands of seedlings per acre were established on most of the open areas of the ponderosa pine forests. While natural mortality of trees overtopped by their neighbors

occurs with most species of trees, this has happened very slowly in the 1919 seedling stands. A report in 1960 stated that 9000 stems per acre was "probably more or less representative of the density of pine thickets in the White Mountains" at age 38 (Cooper, 1960). A tally of dense "doghair" near Flagstaff at age 60 in 1979 showed the following distribution by diameter classes:

Diameter Class (inches)	Number of Trees Per Acre
1	1043
2	902
3	618
4	333
5	218
6	114
7	74
8	52
9	26
10	13
11	9
12	3
13	3
TOTAL	3408

Average diameter 3.3", 204.5 sq. ft. basal area; largest 150 trees, average diameter 8.5", 59.5 sq ft. BA

Although some trees grew well on this acre, the many small trees have been using water and nutrients and have restricted the growth of the larger trees. For example, in this illustration the 300 largest trees range from 5 to 13 inches in diameter and average 7.4". If the stand had been precommercially thinned to 300 trees per acre at age 15, we might reasonably expect it to average 11" in diameter at age 60.

¹Presented at the Symposium on Multiresource Management of Ponderosa Pine. (Northern Arizona University, Flagstaff, November 14-16).

²Ernest A. Kurmes is a Professor in the School of Forestry, Northern Arizona University, Flagstaff, Ariz.

History of Thinning in the Southwest

The earliest recommendations for thinning were made by G.A. Pearson, research forester at the Fort Valley Experimental Forest. Thinning always involves some compromise between diameter growth and natural pruning and form. Pearson's attitude was expressed as follows:

"During the pole stage, when the stems are shaping up, diameter growth is secondary to form and natural pruning. Dense stocking should be the rule. Overstocking in this stage is preferable to understocking, because in the former case, dominants usually assert themselves. If, as a last resort, thinning becomes necessary, removal of only enough stems to encourage the development of dominants will break the deadlock." (Pearson, 1950, page 29).

Uniform thinning had been the rule but very little had been done. Beginning in the 1930's, Pearson recommended a very conservative form of crop tree thinning involving only the removal of competing trees very close to the selected crop trees. Crop tree thinning developed as an economical way to obtain the benefits of thinning at a time when it could be accomplished only by chopping down the trees to be removed. Pearson (1935) contended that it took 30 man-hours of labor per acre to uniformly thin a pole-sized stand while only 8-3/4 hours would have been required for a crop tree thinning. Although he acknowledged the role of deficient soil moisture in limiting tree growth, Pearson felt so strongly about the beneficial effects of competition on stem form and pruning young stands that he did not recommend thinning around dominant trees, and suggested removing only trees whose crowns would touch those of selected codominant and intermediate crop trees. Heavier thinnings to stimulate diameter growth were recommended after the trees reached commercial size of 12" in diameter and 40 to 50 feet in height. Pearson's influence on silvicultural practice in the Southwest was very great and little other thinning research was done during this time.

After Pearson's death in 1949, other foresters began to recommend earlier, heavier, uniform thinning of dense pine stands. In 1954 E.M. Gaines and E.S. Kotok of the Rocky Mountain Forest and Range Experiment Station published their suggestions, based on a study of all the available data from thinning experiments in the Southwest. The expected development of a market for pulpwood was economically encouraging for uniform thinning. Their recommendations were to leave 600 trees per acre in a precommercial thinning, which would be allowed to grow to an average diameter of 7 inches (160 square feet of basal area) followed by commercial thinnings with a residual basal area of 80 square feet.

The U.S. Forest Service followed this guideline for many years, but modified it in doing precommercial thinnings by leaving all trees 5" and larger with the thought that these trees could soon be cut in a commercial pulpwood thinning. As a result, many stands were left with much more than 80 square feet of basal area per acre. Because pulpwood removal has proceeded much more slowly than was expected, some of these stands have never been thinned a second time.

In 1962 the Rocky Mountain Forest and Range Experiment Station established the Taylor Woods thinning plots near Fort Valley (Schubert 1971; Ronco et al. 1985). These plots include 3 replications of 6 different growing stock levels (GSL), ranging from an extreme of excessively heavy thinning (30 GSL) to one of very light thinning (150 GSL). Growing stock levels are identified by numbers representing the residual basal area after thinning when the stands average 10 inches or larger at breast height. When the average diameters of the stands are less than 10 inches lower residual basal areas are required, as indicated in figure 1. This heavier thinning in stands with low average diameters was intended to allow for a reasonable growth rate up to the time the stand could be thinned commercially.

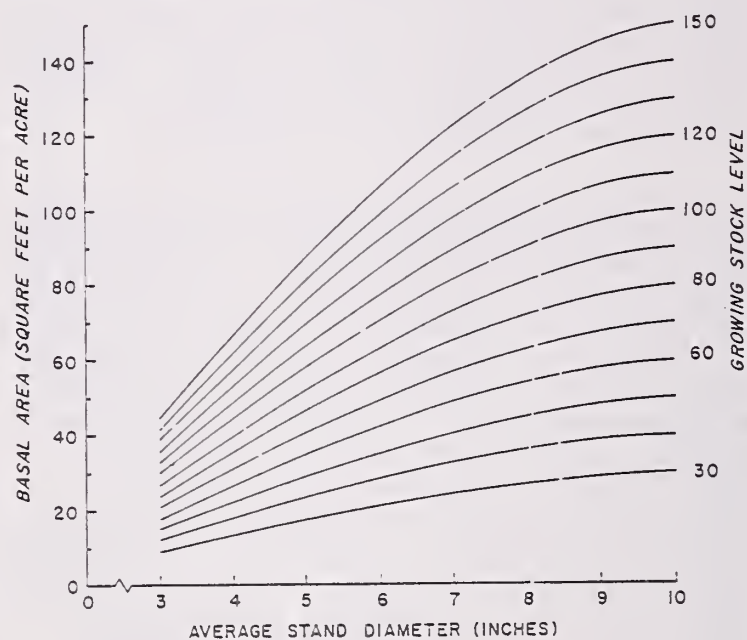


Figure 1. Basal area after thinning in relation to average stand diameter. (Modified from Myers, 1967.)

Based on ten-year results from Taylor Woods, the Southwestern Region of the U.S. Forest Service adopted GSL as a guide to precommercial thinning. The recommended GSL varied with site index: site index 81 or more - GSL 100, site indexes 61 to 80 - GSL 80, site indexes 60 or less, GSL 60 (USFS 1977). Within a few years the Forest Service developed thinning schedules which left only 275 trees per acre in precommercial thinnings and then followed GSL curves. This eliminated the variation

in average spacing with different average stand diameters, simplifying the directions for thinning crews. It also avoided the retention of excessive numbers of trees in stands with very small average diameters. However, it was shortly determined that leaving only 275 trees per acre on very good sites cost a potential commercial thinning, so the residual number of trees was raised to 325 on areas with a site index greater than 79 (USFS 1981). On these highest sites, the stand was grown at GSL 80 after the first commercial entry, while stands with site indexes between 66 and 79 were managed at GSL 60 and those below site index 66 at GSL 50.

More recently (USFS 1985), a new set of stocking charts for southwestern ponderosa pine has been developed based on the Gingrich stocking guide (1967). For areas with a site index equal to or greater than 70, precommercial thinning to 325 trees per acre is recommended, while 275 TPA is recommended for stands with a site index below 70. Upper and lower limits of the management zone are defined as densities relative to average maximum density, a curve based on Reineke's stand density index (Reineke 1933). The major advantage of these curves is that they allow for increasing residual basal areas in stands above 10 inches mean diameter.

Thinning trends in the southwest have followed trends elsewhere in the United States. Precommercial thinning has become heavier and later thinnings follow a line of increasing residual basal area, with some variation allowed for differences in site. As more data from thinning studies become available, we can expect to see further refinements in stocking guides for southwestern ponderosa pine.

LITERATURE CITED

- Cooper, Charles F. 1960. Changes in vegetation, structure, and growth of southwestern pine forests since white settlement. *Ecological Monographs* 30:129-164.
- Gaines, Edward M. and E.S. Kotok. 1954. Thinning ponderosa pine in the southwest. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Station Paper No. 17. 20 pp.
- Gingrich, Samuel F. 1967. Measuring and evaluating stocking and stand density in upland hardwood forests in the central states. *Forest Science* 13:38-53.
- Myers, Clifford A. 1967. Growing stock levels in even-aged ponderosa pine. USDA Forest Service, Rocky Mt. Forest and Range Expt. Station, Research Paper RM-33. 8 pp.
- Pearson, G.A. 1935. Timber stand improvement in the southwest. *Journal of Forestry* 33:128-132.
- _____. 1950. Management of ponderosa pine in the southwest. USDA Forest Service, Agriculture Monograph No. 6. 218 pp.
- Reineke, L.H. 1933. Perfecting a stand-density index for even-aged forests. *Journal of Agricultural Research* 46:627-638.
- Ronco, Frank Jr., C.B. Edminster, and D.P. Trujillo. 1985. Growth of ponderosa pine thinned to different stocking levels in Northern Arizona. Rocky Mountain Forest and Range Experiment Station, Research Paper RM-262. 15 pp.
- Schubert, Gilbert H. 1971. Growth response of even-aged ponderosa pines related to stand density levels. *Journal of Forestry* 69:857-860.
- USDA Forest Service. 1977. Forest Service Manual. FSM 5/77 SUPP 22 SFNF, 2476.42 - Precommercial Thinning. 3 pp.
- _____. 1981. Forest Service Manual, Albuquerque, New Mexico. Interim Directive No. 12, October 2, 1981. 2471.32 - Thinning. 8 pp.
- _____. 1985. Cutting Methods Handbook. R-3 FSH 9/85 AMEND 6 91.1--1 to 10: 91.11--1 to 3.

Historical Effects of Forest Management Practices on Eastside Pine Communities in Northeastern California¹

William F. Laudenslayer Jr.,² Herman H. Darr,² and Sydney Smith³

Abstract.--The eastside pine regions of northeastern California, characterized by stands of ponderosa (Pinus ponderosa) and Jeffrey (P. jeffreyi) pines, have long been influenced by timber harvest, fire suppression, and domestic livestock grazing. These activities have substantially altered the structure and composition of eastside pine stands, and will affect options for management in the future. Before settlement by emigrants (beginning about 1850), eastside pine stands were commonly composed of relatively open stands of large ponderosa or Jeffrey pines, sometimes mixed with other coniferous species. The undergrowth generally consisted of perennial bunchgrasses with relatively few shrubs, principally big sagebrush (Artemisia tridentata var. vaseyana) and bitterbrush (Purshia tridentata). Low intensity ground fires were frequent enough to maintain most of the stands in an open "parklike" condition. Alteration of eastside pine stands by European settlers commenced in the 1880's with intensive logging, fire suppression, and livestock grazing, and these activities continued to increase after World War I. As a result, the eastside pine plant communities have been substantially altered. Eastside pine stands today are more densely stocked with smaller diameter trees. Canopy values for trees and some shrubs are greater. At higher, moister elevations, California white fir (Abies concolor var. lowiana) encroaches on eastside pine, whereas on lower, drier sites, western juniper (Juniperus occidentalis) invades pine stands.

INTRODUCTION

Characterized by Jeffrey and ponderosa pine forests, the eastside pine region in California lies at elevations between 4,000 and 6,500 ft. east of the Sierra Nevada-Cascade crest (McDonald 1983, Fitzhugh 1988). Eastside

pine stands are generally dominated by ponderosa (Pinus ponderosa) or Jeffrey (P. jeffreyi) pines, with lesser acreages dominated by Washoe pine (P. washoensis). Associated tree species include California white fir (Abies concolor var. lowiana), western juniper (Juniperus occidentalis var. occidentalis), and lodgepole (P. contorta) and sugar (P. lambertiana) pines (McDonald 1983, Fitzhugh 1988). A variety of young trees, shrubs, and grasses can be found in the undergrowth.

Eastside pine has been extensively altered since settlement of the eastside pine region in California by emigrants from Oregon and the eastern United States (Pease 1965). Timber harvest practices plus other resource uses, such as grazing of domestic livestock and fire suppression, have combined to alter the presettlement composition and structure of the eastside pine forest. Although some of these changes have been documented, impacts of these activities on coniferous forests in northeastern California are not well known (Rundel et al.

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² William F. Laudenslayer, Jr. is a Wildlife Biologist and Herman H. Darr is a Logging Historian and Volunteer attached to the Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Fresno, Calif.

³ Sydney Smith is an Ecologist with the Modoc National Forest, Forest Service, U.S. Department of Agriculture, Alturas, Calif.

1977). This paper describes the composition and structure of eastside pine at the beginning of the settlement period (about 1850), the major demands on eastside pine and associated vegetation, how eastside pine changed through time, and the current composition and structure of eastside pine stands.

STUDY AREA AND METHODS

Our study area is the northeastern corner of California, including all or most of Modoc and Lassen Counties, and the eastern portions of Siskiyou and Shasta Counties (fig. 1). Historical information for the study area on presettlement composition and structure of eastside pine, and on the activities that altered it, was collected from journals from the fur-trapping, emigrant, and settlement periods; histories of specific geographic areas; historical photographic files; and other sources. Where available and appropriate, information from pine forests in adjacent areas, such as Oregon, was used. Information on current composition and structure of eastside pine was taken from three sources: current forest land management planning data bases, and

data from the eastside pine ecological classification work and the ongoing investigations of the relationship of birds to snag densities in eastside pine.

RESULTS

Presettlement Eastside Pine

Historical Accounts

Several accounts, from the mid- to late 1800's, provide tantalizing clues of the appearance of eastside pine before settlement. Unfortunately, these reports include little quantification of the composition or structure of the forest. Bidwell (1964), a member of a very early wagon train to California, reported on the characteristics of eastside pine between Walker Lake and the crest of the Sierra Nevada. On 17 October 1841, Bidwell commented that they "passed down and up thro' forests of pine, fir, cedar &c; many of the pines were 12 ft. in diameter and no less than 200 ft. high." On 18 October 1841, when his party was just east of the crest of the Sierra Nevada, he noted that "cedars of uncommon size, pines, the most thrifty, clothed the mountains (one pine, as it was near our camp, was measured. Though it was far from being the tallest, it was 206 ft. high.)"

Hastings (1932), in his promotional guide to Oregon and California, noted that the California mountains have "a great abundance of good timber" (Hastings 1932: 71). Virgil K. Pringle, a member of an emigrant train, reported on 20 September 1846, in the vicinity of Fandango Pass in the Warner Mountains, that their camp was "in a beautiful plain surrounded by stately pine and cedar" (Helfrich 1971: 63). Bryant (1985), part of an emigrant train traveling along the Truckee River, noted on 23 August 1846 that he "passed several yellow-pine trees in the bottom, of large dimensions, the trunk of one of them measuring eighteen feet in circumference"... "in front of us, to the west, there is an elevated range of densely timbered mountains." Again, on 24 August, Bryant observed that "mountains are covered with a thick growth of tall and symmetrical timber. Among the varieties of trees I noted the yellow and white-pine, the fir, the common red cedar, and the Chinese *arbor vitae*. Many of the firs and cedars are 200 feet in height, with a diameter at the trunk of six or eight feet, beautifully tapering to a point."

Howell, a member of an emigrant train passing through Fandango Valley on 4 July 1849, recorded that there was "heavy pine timber" (Helfrich 1971: 68). Bruff (1949) noted in his diary, while crossing the Warner Mountains on 30 September 1849, that there was large timber on the mountain ahead (Warner Mountains), and after he had reached the top of the pass and begun the western descent, on 3 October 1849, he recorded that the hills were "thickly timbered with firs and other kinds of tall pine trees."

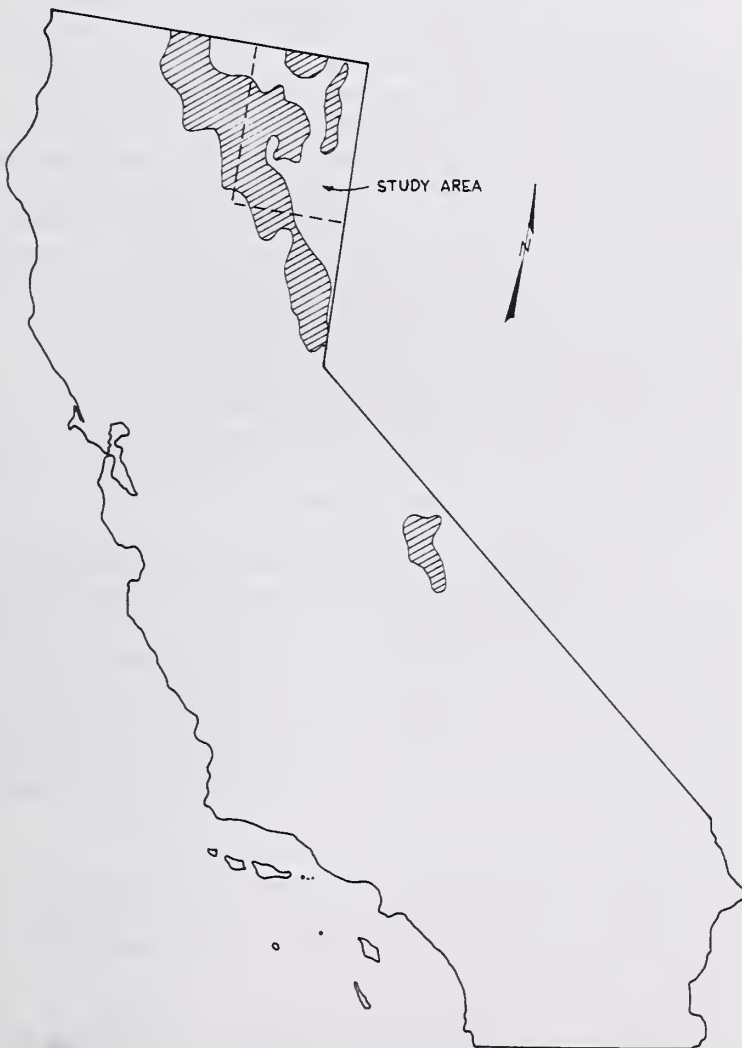


Figure 1.--The eastside pine study area is indicated by the rectangle bordered by dashed and solid lines. Areas filled by parallel lines indicate the distribution of eastside pine in California (Fitzhugh 1988).

On 10 October 1849, Bruff observed, probably in the vicinity of Adin Pass, that there were numerous oaks among pines.

Beeson, on 19 August 1853 in Fletcher Creek Canyon, noted in his diary that the canyon was rough and rocky and contained a great deal of timber (Helfrich 1971: 76). Mrs. P. S. Terwilliger describes eastside pine forests at several locations along the Applegate Emigrant Trail. On 28 September 1854, while her emigrant train was in the Warner Mountains, she noted that they camped on the "edge of great pine wood" (Helfrich 1971: 68). On 29 September 1854, she described Fandango Valley as having "some fine timber" (Helfrich 1971: 69). Later, on 2 October 1854 along Fletcher Creek on Devil's Garden, Mrs. Terwilliger observed "Plenty of pine wood" (Helfrich 1971: 76). Fariss and Smith (1974), in their history of counties in northeastern California, reported that the growth of conifer trees, along the western border of Lassen County, was sufficient to produce millions of board feet of the best quality timber annually.

Stand Structure of Presettlement Eastside Pine

Although early historical accounts give clues to the appearance of eastside pine, they do not provide a clear view of the characteristics of presettlement eastside pine. Examination of forestry reports from the turn of the century, historic photographs depicting eastside pine and various logging scenes, and present-day photographs of eastside pine stands that have not been substantially altered provides more detailed information about the composition and structure of eastside pine forests. There is little doubt that eastside pine forests were highly variable in structure and composition (figs. 2, 3) (Burcham 1959, Moir and Dieterich 1988). However, now we do not have information to describe these variations. Structure and composition of ponderosa pine



Figure 2.--Eastside pine stand in the western part of the Modoc National Forest, California, about 1930 (USDA Forest Service photograph).



Figure 3.--Eastside pine forest near Happy Camp Guard Station, California, about 1930 (USDA Forest Service photograph).

forests in California were generally related to the availability of soil moisture in summer and fire history (Rundel et al. 1977).

Before settlement, eastside pine generally consisted of either monotypic stands or mixtures of ponderosa and Jeffrey pines. Pine stands also existed as mixtures with other conifers, especially with California white fir; both sugar pine and incense cedar (*Libocedrus decurrens*) were infrequent associates (Berry 1917). Other tree species found in association with ponderosa and Jeffrey pine included Washoe, lodgepole, and western white (*Pinus monticola*) pines, red fir (*Abies magnifica*), Douglas-fir (*Pseudotsuga menziesii*), western juniper, and California black oak (*Quercus kelloggii*) (Smith et al. 1988). Distribution of trees varied from scattered patches of trees to virtually continuous stands (Pease 1965).

Structurally, eastside pine was generally composed of large trees that were widely scattered. Canopy closures tended to be relatively low, probably ranging from about 30 percent on dry sites to 80 percent in the most productive areas (Smith et al. 1988). Berry (1917) reported that yellow or Jeffrey pine trees are often only four-log trees (a standard log was 16 ft. long), suggesting that mature trees generally were shorter than 100 ft. Stands of ponderosa pine in Oregon consisted of small groups of trees of similar ages; however, the groups varied greatly in age (Munger 1917, Franklin and Dyrness 1973).

Munger (1917) reported that fully stocked stands had from 20 to 30 trees (> 12 in. diameter) to the acre; however, densities were highly variable. Basal areas ranged from 56 to 100 ft.² per acre, and quadratic mean diameters (qmd) ranged from 16 to 27 in. diameter at breast height (dbh). Volume per acre was also highly variable. Berry (1917)

noted that the average volume of eastside pine was 11,000 board feet per acre, and Munger (1917) published values of volumes, ranging from 14,000 to 25,000 board feet per acre.

Undergrowth vegetation was principally composed of perennial bunchgrasses with lesser amounts of shrubs especially where the canopy was more open. Then, as now, Idaho fescue (*Festuca idahoensis*) was the most abundant of the bunchgrasses at some sites. Lesser amounts of bluebunch wheatgrass (*Agropyron spicatum*), Sandberg bluegrass (*Poa sandbergii*), squirreltail (*Sitanion hystrix*), and Ross's sedge (*Carex rossii*) were often present. Common graminoids in moister ecological types were Wheeler bluegrass (*Poa nervosa*) and needlegrasses (*Stipa* sp.).

Common shrubs included mountain big sagebrush (*Artemisia tridentata* var. *vaseyana*), rabbitbrush (*Chrysothamnus nauseosus*), bitterbrush (*Purshia tridentata*) (Pease 1965), mountain mahogany (*Cercocarpus ledifolius*), pallid serviceberry (*Amelanchier pallida*), rabbitbrush goldenweed (*Haplopappus bloomeri*), greenleaf manzanita (*Arctostaphylos patula*), pinemat manzanita (*Arctostaphylos nevadensis*), snowbrush (*Ceanothus velutinus*), and squaw-carpet (*Ceanothus prostratus*) (Applegate 1938, Smith et al. 1988).

Applegate (1938) noted that bitterbrush was practically the only shrub found in some areas of eastside pine. Smith (1989) provided information on the potential canopy structure of presettlement eastside pine based on an evaluation of existing, but relatively unaltered stands; most of the stands examined, however, had not been burned in 60 to 70 years. Smith concluded that shrub cover exceeded 10 percent where overstory canopy closures ranged from 35 to 55 percent, whereas shrub cover was less than 10 percent where tree canopy cover averaged about 65 percent.

Eastside pine ranged over elevational and latitudinal gradients; on the edges of its range, areas of transition with adjacent plant communities existed. At higher and moister sites, eastside pine graded into mixed conifer with species such as California white fir and incense cedar, whereas at lower and drier sites, pines became mixed with western junipers, especially on rocky sites.

Activities Influencing Eastside Pine Forests

Settlement of Northeastern California

Several groups of American Indians inhabited the eastside pine region in northeastern California when settlement was initiated about 1850. Brown (1945) stated that the presettlement Indian population may have been equal to or even exceeded the combined Indian and non-Indian population of the area in 1945. One of the major impacts of Indians on

the land may well have been their use of fire to deliberately burn off the grass and shrub vegetation (see the section entitled Wildfire and Its Suppression for a discussion of the use of fire by American Indians).

The first visitors of European extraction to the eastside pine area of northeastern California included fur trappers, livestock drovers, and military explorers. Fur trappers entered the study area first around 1828 or 1829 and followed the Pit River in their travels between the Hudson Bay Company trading posts in the Pacific Northwest and the Sacramento Valley (Brown 1945, Pease 1965). Apparently they trapped while traveling through the region. They did not, however, collect many furs. In 1834, Ewing Young drove livestock purchased in northern California north into Oregon across the western portion of the eastside pine region (Pease 1965).

U.S. military explorations of the area began in 1841 when Charles Wilkes passed by the Pit River as his party traveled between the Columbia River and San Francisco Bay. John Charles Fremont may have entered Surprise Valley during his travels in the area in 1843. The first description of the eastside pine region that included specific details was written by Fremont who, in 1846, mapped and named topographic features in the vicinity of Tule Lake (Brown 1945). Later explorations by W. H. Warner and R. S. Williamson in 1849 and two of the 1854 Pacific Railroad Explorations (led by E. G. Beckwith to the south of the Warner Mountains and R. S. Williamson and H. L. Abbot to the north of the Pit River and beyond Klamath Lake) provided much needed information about northeastern California.

The earliest emigrant trails to Oregon were difficult for pioneer travelers (fig. 4). In search of an easier route, the Scott-Applegate party in 1846 explored a trail from southern Oregon that intersected the California trail along the Humboldt River in northwestern Nevada (Brown 1945, Pease 1965). Emigrant trains to Oregon and California, beginning in late 1846, passed through northeastern California using the Applegate Trail and later, the Lassen and Nobles trails. Most of these travelers crossed the Warner Mountains using Fandango Pass and then moved down the Pit River (Lassen Trail) or crossed farther to the south from Honey Lake and then to the north of Mt. Lassen (Nobles Trail).

Development of the study area began in the late 1850's with the establishment of settlements in the Fall River and Honey Lake valleys. Surprise Valley was first settled in the early 1860's. Growth of the area was rather slow. The population of Modoc County grew slowly from 4,399 (1880), 6,191 (1910), 8,713 (1940), 9,678 (1950), 8,303 (1960) (Pease 1965), to 8,425 in 1980. The economy of the area depended largely on agriculture until about 1920, when increasing amounts of finished lumber

and saw logs began to be exported from the local area, and the importance of timber production to the local economy substantially increased (Pease 1965).

Transportation systems developed slowly in northeastern California (fig. 5). Initially, transportation was by wagon over primitive roads, some of which followed the early emigrant trails. In 1881, the predecessor to the Nevada-California-Oregon (NCO) Railway initiated construction of a narrow gauge line to the Columbia River from Reno, Nevada. Honey Lake was reached in 1890, and construction ceased for some 10 years because funding for construction was not available. Alturas was finally reached in 1908 and Lakeview, Oregon, the terminus, in 1912 (Myrick 1962, Barry 1982). This railroad accessed only the eastern edge of the study area.

The rail network in northeastern California was developed more fully in the 1920's and 1930's. By 1930, the Southern Pacific Company had widened the old NCO Reno-to-Lakeview line to standard gauge and constructed a new line from Alturas to Klamath Falls, Oregon. In 1931, the Great Northern Railway line from Klamath Falls and the Western Pacific Railroad branch from Feather River canyon met near Bieber. The rail transportation network was completed with the addition of numerous logging railroads. One was

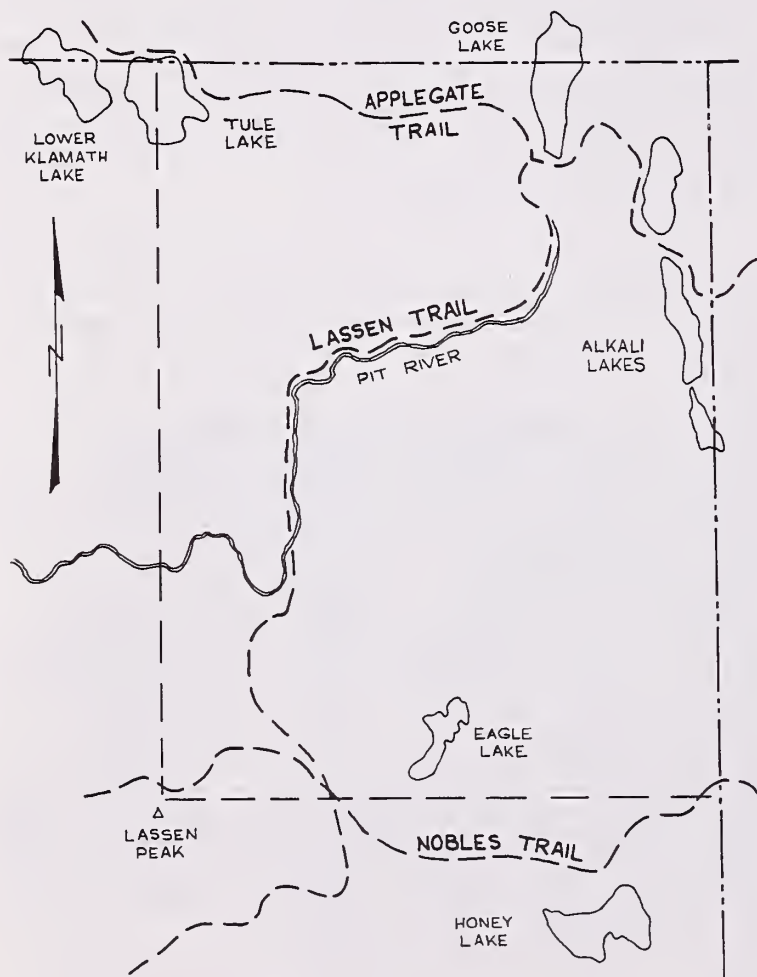


Figure 4.--The eastside pine study area indicating the Applegate, Lassen, and Nobles emigrant trails.

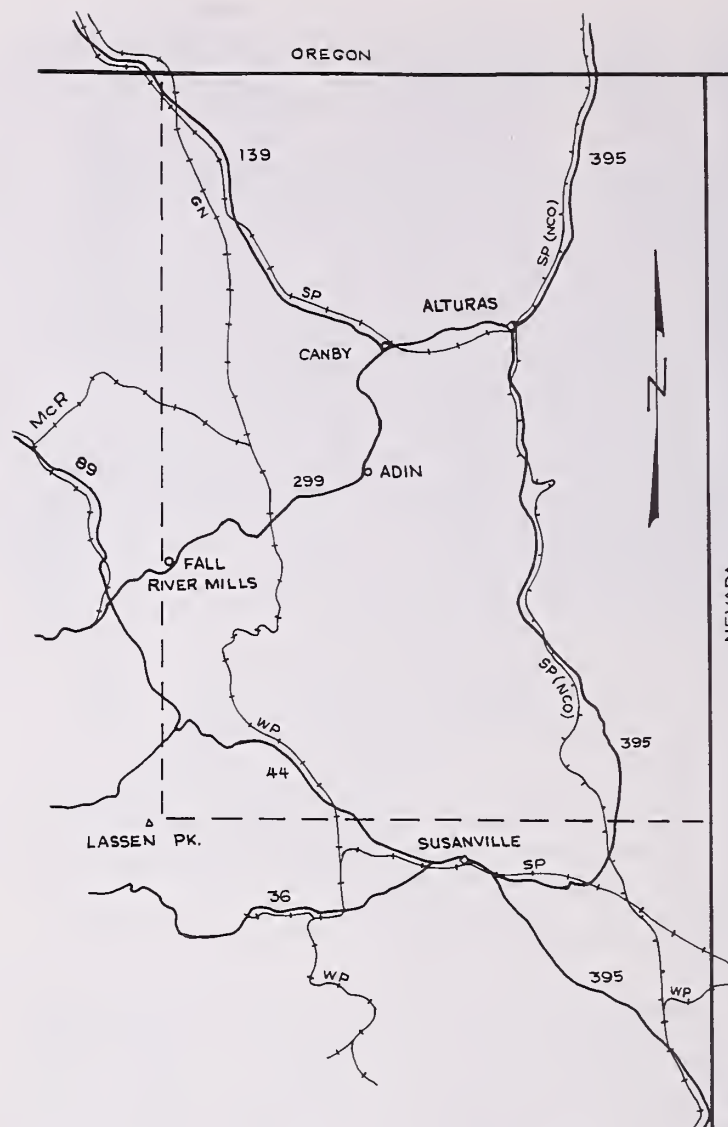


Figure 5.--The eastside pine study area indicating major towns, common-carrier railroads, and major highways. Common-carrier railroads are: GN = Great Northern (now Burlington Northern), SP (NCO) = Nevada-California-Oregon (now Southern Pacific), McR = McCloud River, SP = Southern Pacific, and WP = Western Pacific. Major highways are: 36 = Calif. 36, 44 = Calif. 44, 89 = Calif. 89, 139 = Calif. 139, 299 = Calif. 299, and 395 = U.S. 395.

the Long-Bell Lumber Company whose main extended from near the Pit River north of Lookout to the Southern Pacific mainline at Weed (Myrick 1962, Shoup and Baker 1987). Another was the McCloud River Railroad connecting the areas around Whitehorse and Burney with the Southern Pacific near McCloud. Others were the Great Northern near Lookout (Myrick 1962, Hanft 1971), the Red River Railroad with an electrified main line in the Chester/Westwood area (Myrick 1962, Hanft 1980), and other logging lines extending into the woods from connections with the Western Pacific (Myrick 1962).

Highways for motorized traffic have also played an important part in the recent development of the area. Early roads followed the emigrant trails or were constructed to

connect early towns (fig. 4). Two-lane federal and state highways access most major towns in the study area, and additional county and forest roads provide access to the rural areas (fig. 5).

Timber Harvest

Timber harvesting, from the initial settlers on, was an important activity in northeastern California. Wood was harvested for boards and shingles to construct dwellings, barns, and other structures. Initially, structures were built of logs. However, within a very short time, mills were established and pine boards and shingles became the preferred building materials. Fuelwood was used for heating, cooking, and fueling steam-powered equipment. Other wood products from eastside pine include timbers and planks for use in the mines, water ditches, and railroads (Berry 1917, Pease 1965), and box shooks, coffin material, and sash and door stock.

Initially, timber products were taken from forests close to centers of development. In 1880, three mills were operating in the Warner Mountains to supply wood products to Surprise Valley and a fourth mill served the Alturas area. Early mills were water powered and were located in canyons to utilize water power resources. The mills were quite small and were situated close to the timber to be cut and the community to be served because of the lack of adequate transportation. By 1912, 5 million board feet of lumber was harvested yearly to satisfy local demand.

Beginning about 1920, mills increased in size and began to export timber to areas outside the eastside pine region. Finally, by 1935, the timber industry generally became economically dependent on export sales. Consequently, mills became even larger, to exploit the relatively large sales of timber or the large expanses of private timberlands that were then owned by only a few companies. By 1940, nine mills in Modoc County produced 107 million board feet of lumber. A similar amount of lumber was produced by mills in Siskiyou County, California, or at nearby mills in Oregon from saw logs harvested in Modoc County. By 1963, only 78 million board feet of lumber were exported from four mills in Modoc County (Pease 1965). Currently, some 20 million board feet of lumber are milled each year in Modoc County.

Timber stocks have declined substantially since the 1930's. By 1934, 52,250 acres of timberland in Modoc County had been cut over. The total number of acres that had been harvested reached 136,750 acres by the end of 1938 and 259,750 acres by the end of 1943 (Brown 1945). At present, virtually all of the virgin timber has already been harvested, and cutting is taking place in stands that had been cut over earlier in this century.

Harvest practices varied through time and depended, to some extent, on the landowner. Generally, only merchantable trees were harvested. Logging and market conditions varied considerably and, therefore, the definition of merchantability varied in time and from place to place (Berry 1917). Those trees not considered merchantable, because the species was not desired or the wood was defective, generally were not cut. Only about 5 percent of ponderosa pine generally was defective (Berry 1917). Preferred species for harvest were, and still are, pines; recently, California white fir has become a more important component of the timber supply (Pease 1965).

The sizes of trees left after harvest depended on the tree species found on the site. Pines with diameters inside the bark of greater than 14 to 15 in. were usually harvested. Some companies took all trees that met the appropriate size criteria, whereas other companies harvested only pines and the best of the firs and incense cedars (Berry 1917). As an example, USDA Forest Service reports supporting the transfer of cutover eastside pine lands from the Long Bell Lumber Company to the Forest Service documented that California white fir and incense cedar generally remained after harvest and, on some sites, a residual overstory of pine was left⁴. In more recent years, overstory removal of only the largest trees has become more common.

Stumps from 16 to 36 in. in height usually remained after harvest (Berry 1917). High stumps were left because the lowest portions of the trees were commonly defective from fire scarring or accumulation of pitch from low intensity burns.

Livestock and Range Management

Early livestock operators concentrated on raising cattle along the meadow lands of the Pit River. Livestock production, during the years immediately after settlement, was for local consumption, and excess production was added to the herds. By 1910, the livestock industry had increased substantially.

In 1880 there were 16,000 beef cattle, 23,000 resident sheep, and 6,000 horses in Modoc County. In 1909, there were 44,000 beef cattle, 76,500 resident sheep, and 15,000 horses (Pease 1965). By this time, livestock operations had come to depend on the adjacent uplands for summer graze so that the meadows in the vicinity of the Pit River and its tributaries could be used for production of hay for winter feed and cash crops. About 1880, sheep drovers from the Sacramento Valley, Nevada, and Oregon began to

⁴ Goldsmith, B. C. 1933. unpublished land valuation reports [on file at Klamath National Forest Supervisors Office, Yreka, Calif.]

graze large transient flocks in eastside pine forests and on the adjacent grasslands.

Intensive, unmanaged grazing of the eastside pine forests and adjacent rangelands resulted in the decline of perennial bunchgrasses and increase of the invasive cheatgrass (*Bromus tectorum*) as well as shrubs and small trees. At the time of the first settlements in the area, extensive acreages of bunchgrass had little or no junipers or sagebrush. However, junipers and sagebrush increased substantially in the period during and after unmanaged grazing, especially of sheep (Caldwell 1985). The increase in woody vegetation is also related to fire exclusion, and the removal of fine fuels by livestock.

Controls were placed on the numbers of animals grazed and on grazing practices after establishment of the Forest Reserves (1904) and the Grazing Service of the U.S. Department of Interior (1935) (Brown 1945). These controls have resulted in an improvement in some areas since then. In the absence of fire, lower, more xeric stands of eastside pine and vast acreages of adjacent rangeland are being invaded by western juniper, causing serious deterioration of range condition in many areas.

Wildfire and Its Suppression

Fires, both natural and human-caused, have affected structure and composition of eastside pine in California. Ponderosa and Jeffrey pine are resistant to fire because of a thick, dead layer of outer bark even at small diameters. Other species, such as California white fir, do not develop this thickened bark and are more easily killed by the lowest intensity ground fires (Hall 1977).

Lightning-caused fires are frequent in the study area. The Modoc National Forest has recorded over 5,000 lightning-caused ignitions since 1913 (Elizabeth Cavasso, personal communication). Under presettlement conditions, fires generally do not appear to have been catastrophic but occurred frequently enough to reduce the undergrowth trees and shrubs substantially. Franklin and Dyrness (1973) reported that fire intervals in ponderosa pine in Oregon ranged from 8 to 20 years. These fires generally were of low intensity and were confined to the ground.

Fire can substantially reduce shrub cover and increase grass cover especially on more xeric sites. Fires before settlement regulated regeneration of pine and resulted in open, grassy, parklike stands (Franklin and Dyrness 1973). Munger (1917) noted that western yellow pine (= ponderosa pine) was fire resistant because destructive crown fires in the typically open stands were rare; most fires were confined to the surface consuming grass, needles, and shrubs. Ground fires also caused damage to stands by directly killing a few trees, and

scarring the butts of merchantable trees (Munger 1917).

The effects of fires set by native Americans in northeastern California are not well understood. Bean and Lawton (1973:v) stated that "burning was the most significant environmental manipulation employed by California Indians." Burcham (1959) concluded that fire was used by Indians to aid in hunting in northeastern California. Indians used fire in northeastern California to aid in hunting animals and improve wild seed crops (Lewis 1973). Lewis also reported that Indians in the lower Pit River Valley burned mixed chaparral in the spring; however, he did not postulate an objective for burning. Pease (1965) concluded that extensive burning would probably not improve habitat quality and animal numbers and, therefore, it is not likely that extensive planned burns took place. It is likely that Indians used fire to alter the vegetation for hunting and gathering purposes. It is not clear to what extent, either in frequency or area of extent, fire was used in our study area.

Fires appear to have increased through time both in severity and extent (Brown 1945). Kinney (1900) commented that it was customary to exaggerate the amount of damage done by fire and that "The majority of forest fires in California do not destroy the forests they traverse. Damage is done and much waste takes place, especially in territory long protected" (Kinney 1900:54).

Brown (1945) noted that in the late 1800's, newspapers in northeastern California made only casual mention of wildfires. Occasionally, property owners did group together and fight those fires that threatened their properties. Increased logging operations resulted in the increase of slash and fire hazards. Invasion of eastside pine lands by cheatgrass, and increase of woody shrubs, dense thickets of young trees, and accretion of woody debris have increased the probability of catastrophic fires.

Presettlement vs. Current Stand Conditions

Comparing presettlement and current characteristics of eastside pine is difficult because of the paucity of information available. Munger (1917) described three stands of eastside pine from central and south-central Oregon; we surmised from their locations that the stands were analogous to eastside pine stands in northeastern California. Munger's data imply that these stands were in an unmanaged state, and that they possibly exhibited "old-growth" conditions.

The stands in Oregon had quadratic mean diameters that ranged from 16.2 to 27.1 in.² dbh. Basal areas ranged from 54 to 125 ft.² per acre. Trees per acre for all species ranged from 13.9 to 76.7. The number of trees per acre

with diameters greater than 25 in. ranged from 18 to 64 percent of the total. The number of trees per acre with diameters greater than 30 in. ranged from 9 to 39 percent of the total (Munger 1917).

In contrast, later seral stage stands, currently occurring in **northeastern California**, have qmd's that range from 17.9 to 21.8 in. dbh, and basal areas that range from 122 to 159 ft.² per acre. Trees per acre range from 74 to 101. The number of trees per acre with diameters greater than 24 in. range from 5 to 22 percent of the total, and the number of trees per acre with diameters greater than 30 in. range from 2 to 9 percent (Smith 1989).

Comparisons between the current and presettlement characteristics of eastside pine forests reveal the following patterns:

- The regional extent of pure eastside pine stands is smaller. Many acres of stands that were maintained by periodic fire have converted in its absence to "eastside mixed conifer" stands of Jeffrey or ponderosa pine mixed with California white fir, western juniper, or lodgepole pine.
- Eastside pine forests today have greater numbers of smaller trees per acre. Larger, older trees (when present at all) make up a much smaller component of each stand. Average stand ages are less, and tree spacings are smaller. Average stand height is less. Tree canopy closure is higher.
- The amount of herbaceous vegetation is lower. Shrub canopy closure is higher in some types. Shrub stands, especially bitterbrush stands, are more decadent.
- The amount of dead and down material is higher. Litter and duff depths are greater. Some data suggest that presettlement stands, with frequent fires, had fewer available nutrients than current stands that have larger amounts of debris and litter (William Hopkins, personal communication). Available water holding capacity may be higher now because of accumulations of litter and duff.
- Susceptibility to high intensity fires is higher because of the fuel buildups and higher stocking. The likelihood of pine forests escaping stand-destroying fires within the 175-226 years necessary for developing old-growth characteristics is low (Moir and Dieterich 1988, Smith 1989).
- Potential for total numbers of snags is higher now, but numbers of snags, especially those with dbh's greater than 15 in. and heights greater than 20 ft., are low because of aggressive snag-removal programs conducted on National Forests since the 1920's and the reduced numbers of larger trees.

- **Susceptibility** to disease and insects is probably greater because of the amount of stress that is on the trees. Stress is often related to stocking levels; the greater the stocking, the greater potential for stress.

CONCLUSIONS

Timber harvest, livestock grazing, and change in fire frequency all have had a substantial effect on both the overstory and undergrowth of eastside pine. Timber harvest has removed many of the large trees and, because pines, such as ponderosa, Jeffrey, and sugar, were desired harvest species, timber harvest has reduced them relative to California white fir and western juniper. Structure of pine stands has also changed. The lack of fire has permitted the establishment of denser thickets of small trees, especially California white fir, in the undergrowth. Juniper has replaced the grass/shrub vegetation on large acreages at the lowest elevational margins of the eastside pine type as a result of livestock grazing and fire suppression. Shrubs have increased at the expense of both the grass/shrub vegetation and the grass undergrowth as well.

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LITERATURE CITED

- Applegate, E. I. 1938. Plants of the Lava Beds National Monument, California. *American Midland Naturalist* 19:334-368.
- Barry, P. 1982. A layman's history of the N-C-O Railway. *Journal of the Modoc County Historical Society* 4:11-63, Alturas, Calif.
- Bean, L. J., and H. W. Lawton. 1973. Some explanations for the rise of cultural complexity in native California with comments on proto-agriculture and agriculture. *Ballena Press Anthropological Papers* 1:v-xlvi.
- Berry, S. 1917. Lumbering in the sugar and yellow pine region of California. 99 p. U.S. Department of Agriculture, Bulletin No. 440. Washington, D.C.
- Bidwell, J. 1964. A journey to California, 1841--the first emigrant party to California by wagon train. 90 p. The Friends of the Bancroft Library, Berkeley, Calif.
- Brown, W. S., Sr. 1945. History of the Modoc National Forest. 87 p. U.S. Department of Agriculture, Forest Service, California Region, San Francisco, Calif.

- Bruff, J. G. 1949. Gold Rush-- the journals, drawings, and other papers of J. Goldsborough Bruff April 2, 1849 - July 20, 1851. G. W. Read and R. Gaines, eds. 793 p. Columbia University Press, New York.
- Bryant, E. 1985. What I saw in California. (reprint of the original edition of 1848). 455 p. University of Nebraska Press, Lincoln.
- Burcham, L. T. 1959. Planned burning as a management practice for California wild lands. 21 p. California Division of Forestry, Sacramento.
- Caldwell, A. W. 1985. A brief history of the Williams Ranch in Black's Canyon. Journal of the Modoc County Historical Society 7:79-91, Alturas, Calif.
- Fariss and C. L. Smith. 1974. History of Plumas, Lassen & Sierra Counties, California and biographical sketches of their prominent men and pioneers. (reprint of the original edition of 1882). 507 p. Howell-North Books, Berkeley, Calif.
- Fitzhugh, E. L. 1988. Eastside pine. p. 58-59. In K. E. Mayer and W. F. Laudenslayer, Jr., eds. A guide to wildlife habitats of California. 166 p. California Department of Forestry, Sacramento.
- Franklin, J. F., and C. T. Dyrness. 1973. Natural vegetation of Oregon and Washington. 417 p. USDA General Technical Report PNW-8. Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.
- Hall, F.C. 1977. Ecology of natural underburning in the Blue Mountains of Oregon. 11 p. U.S. Department of Agriculture, Forest Service, Pacific Northwest Region Publ. R6-ECOL-79-001, Portland, Oreg.
- Hanft, R. M. 1971. Pine across the mountain. 224 p. Golden West Books, San Marino, Calif.
- Hanft, R. M. 1980. Red River. 304 p. Center for Business and Economic Research, California State University, Chico.
- Hastings, L. W. 1932. The emigrants' guide to Oregon and California. (reprint of the original edition of 1845). 157 p. Narratives of the Trans-Mississippi Frontier, Princeton University Press, Princeton, N.J.
- Helfrich, D. 1971. The Applegate Trail. 106 p. Klamath Echo No. 9. Klamath County Historical Society, Klamath Falls, Oreg.
- Kinney, A. 1900. Forest and water. 250 p. Post Publishing Company, Los Angeles.
- Lewis, H. T. 1973. Patterns of Indian burning in California: ecology and ethnohistory. Ballena Press Anthropological Papers 1:3-101.
- McDonald, P. M. 1983. Climate, history, and vegetation of the eastside pine type in California. p. 1-16. In T. F. Robson and R. B. Standiford, eds. Management of the eastside pine type in northeastern California - proceedings of a symposium. Northern California Society of American Foresters Publ. SAF 83-06. Susanville, Calif.
- Moir, W. H., and J. H. Dieterich. 1988. Old-growth ponderosa pine from succession in pine-bunchgrass forests in Arizona and New Mexico. Natural Areas Journal 8:17-24.
- Munger, T. T. 1917. Western yellow pine in Oregon. 48 p. U.S. Department of Agriculture, Bulletin No. 418. Washington, D.C.
- Myrick, D. F. 1962. Railroads of Nevada and eastern California, Volume I. 453 p. Howell-North Books, Berkeley, Calif.
- Pease, R. W. 1965. Modoc County--a geographic time continuum on the California volcanic tableland. 304 p. University of California Publications in Geography, Volume 17.
- Rundel, P. W., D. T. Gordon, and D. J. Parsons. 1977. Montane and subalpine vegetation of the Sierra Nevada and Cascade Ranges. p. 559-599. In M. G. Barbour and J. Major, eds. Terrestrial vegetation of California. John Wiley & Sons, New York.
- Shoup, L. H., and S. Baker. 1987. Speed power, production, and profit: Railroad logging in northeastern Siskiyou County, 1900-1956. The Siskiyou Pioneer 5(10): 5-107. Siskiyou County Historical Society, Yreka, Calif.
- Smith, S. 1989. Fuels management environmental analysis, environmental consequences: the Eastside Pine Ecosystem. 12 p. U.S. Department of Agriculture, Forest Service, Modoc National Forest, Alturas, Calif.
- Smith, S., K. Luckow, and G. Kliever. 1988. Draft guide for the ecological types of the Eastside Pine Ecosystem, Klamath, Modoc, Lassen, Plumas, Shasta-Trinity and Tahoe National Forests. 168 p. U.S. Department of Agriculture, Forest Service, Modoc National Forest, Alturas, Calif.

Some Observations Regarding Growth and Yield of Southwestern Ponderosa Pine and Dendro-Ecological Growth Studies¹

Charles E. Thomas²

Abstract. New politically provocative problems face the forest manager, acid rain, ozone pollutants and global greenhouse effects potentially impact the growth and health of forests. Long term growth records are becoming increasingly important to understanding tree and stand growth trends under changing environmental conditions. Growth and yield studies in Southwest ponderosa pine began with the pioneering work of G. A. Pearson at Fort Valley. A. E. Douglass pioneered the analysis of growth from studying tree-rings in the Southwest's ponderosa. Analyses of dendrochronological data have undergone recent statistical improvement with the incorporation of extensive computer editing and Kalman filter algorithms.

Long-term growth and yield plot installations, dendrochronologies establishing truly long-term growth patterns, mathematical sophistication and statistical consistency must be brought together, if we are to understand management implications for growth of southwestern ponderosa pine in the future human-influenced environment.

INTRODUCTION

There is currently a debate raging over the impact of human made pollutants on forest health. Studies indicate apparent growth (health) declines in forests of North America and Europe. The techniques to investigate these declines are in rapid development; several approaches have proven fruitful. Some of these declines have been well documented with long tree-ring chronologies (see references in Van Deusen In Press). In other areas, however, purported declines have been based on periodic remeasurement of inventory plots. Initially, these latter 'declines' failed to account for climate factors, but were based instead on a simple comparison of growth rates for two periods. Atmospheric pollution ozone or other

anthropogenic causes have received a large portion of the attention in the attempt to assign blame or cause for what remain apparent declines.

Ponderosa pine (*Pinus ponderosa*) has proven to be one of the species that is affected by at least one specific air pollutant, ozone. In the San Bernardino Mountains and Southern Sierras of California documented effects of ozone on growth and/or growth related physiological features of ponderosa have been reported (Miller et al. 1978). The pollutants that have been identified as causal agents in California have been detected in Arizona and New Mexico. Although the levels are generally lower, there are exceptions. SO_x has major point sources and other pollutants are locally important. Mining smelters are the sources of some of the pollutants in Arizona and New Mexico, but automobiles, power plants and other urban sources may also be involved. Air sampling stations established as part of NAPAP (National Air Pollution Assessment Program) near Flagstaff, Prescott, Springerville, and Tucson became part of a data base analyzed by Böhm (1989) that showed some pollutant gases occasionally near chronic levels at more northerly

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²Charles E Thomas is research forester, Southern Forest Expn. Stn., Institute for Quantitative Studies, New Orleans, LA.

sites, while even higher levels occurred at more southerly sites.

One of the research questions posed by the joint USDA Forest Service and EPA Forest Response Program is: "Are changes in forest condition greater than can be attributed to typical trends and levels of natural variability?" The prerequisite for answering this question is that trends and their variability can be quantified. Guessing at a decline in growth will not do.

The past often holds important information for the future, if we are willing to learn from the processes or substance of the past and refuse to let appearances deceive us. In this paper, I will look at some of the historical research into tree growth and explore some of the current efforts to quantify possible anthropogenic pollutant impacts or potential impacts on forest growth that might be useful in the future growth of southwestern ponderosa.

DENDROCHRONOLOGY AND FOREST GROWTH

Arizona is rich in history of the development of two research areas that are of importance to the future management of ponderosa pine for health and timber growth. The pioneering research in forest growth and yield by G. A. Pearson of the US Forest Service on ponderosa pine still provides a resource for those who wish to manage the type for all the multiple resources available from the forest. Pearson's research culminated in 1950 with the publication of *Agriculture Monograph No. 6, Management of ponderosa pine in the southwest*. At nearly the same time in history, A. E. Douglass at the University of Arizona was outlining the principles of dendrochronology: *Climatic Cycles and Tree Growth* appeared in 1919. The two scientists were not linked directly as far as I can tell, but Pearson cooperated with W. S. Glock, a protege of Douglass, in the publication of *Principles and Methods of Tree-Ring Analysis* in 1937.

Development of Dendrochronology

In *Principles and Methods of Tree-Ring Analysis*, the methods developed over the years by Douglass for sampling trees, identifying a variety of ring problems and types, measuring the rings, precisely dating individual rings and trees to climate events such as droughts of specific years and duration are illustrated. Missing and partial ring formation are shown to be suitably accounted for by the methods developed by Douglass. Dendrochronology grew up in arid country, and not under the normal forest-stand, inter-tree competition conditions. It has become increasingly important to be able to examine the long-term growth records available not only in the tree-ring chronologies, but also to be able to understand the effects that forest stand dynamics have on observed patterns in the chronology.

H. C. Fritts (1976) also contributed significantly to the development of tree-ring applications and methods. Improved statistical analyses and measuring techniques were added to earlier methods. Dendrochronologists have come to use a number of techniques for analyzing measurements of tree-ring widths that introduce at least two elements that are disturbing to the statistician. First, there is the uniformitarian assumption. This assumption states that current stand conditions are analogues for past conditions. In fact, competition status fluctuations that are part of stand dynamics may vary with the environmental changes. Second there has always been a subjective component to the treatment of tree-ring analyses. The two notable components of this treatment are the subjective smoothing of long-term record and the statistical "pre-whitening" of the data. While the methods used have sought to follow statistically sound procedures developed for time-series analyses, they continue to rely heavily on a subjective aggregation of methods.

New methods have been developed to provide for time varying parameters and compensate somewhat for the two problems. These new methods will be discussed later.

A recent example of the current application of the traditional dendrochronological method, which relates directly to the concern for atmospheric pollutant and climate influences, is D. A. Graybill and M.R. Rose (1989 in press). These analyses might better be termed dendro-ecological as their principal objective is the influence of the environment on growth rates of forest stands. Analyses of growth trends in conifers for Arizona and New Mexico is presented in a study that was jointly initiated by the FS/EPA.

In the initial stages, several stands were identified as having un-datable periods in the last 30 to 60 years, since up to 40 rings were absent from the chronology. This ring anomaly was totally unexpected because precipitation trends throughout the region show a decline from early in the century reaching a minimum in the '50s and a substantial recovery in the '70s and '80s. Most trees that grew on or above the Mogollon rim demonstrated a "u"-shaped growth curve from the beginning of the century until the present. Trees growing in the Basin and Range region, i.e., south of the Mogollon Rim, from six of seven stands showed no recovery from the period of drought in the '50s.

Regardless of the objections foresters and statisticians have against dendrochronology, the success at determining climatic changes over the past have been truly remarkable. So successful has the science been that it has been used to provide a calibration to the well known carbon-14 dating methods. Recent statistical developments may provide an even richer future for dendro-ecology.

Forest Dynamics and Growth and Yield

Obviously, I'll not cover all the developments in growth and yield, only a brief indication of two historical contributions. Growth and yield studies have long shown that volume increment may not show in direct relation to basal area or radial growth; it may simply retreat up the bole to the base of the live crown. Therefore, an orderly decline in radial growth of trees or stands occurs while volume growth continues unabated. G. A. Pearson's contribution, *Factors Influencing the Growth of Trees*, to *Principles and Methods of Tree-Ring Analysis* (in Glock 1937) pointed out that tree growth is determined by a large number of factors, some working in conjunction with, others in opposition to each other. Pearson described a number of physical and biotic factors and their interrelationships, which foresters recognize influence tree growth. His conclusion reiterated that volume of wood increment is the only true measure of growth. He emphasized the geometric relationships that must mathematically relate diameter growth to volume growth. He pointed out that vigorous young trees may actually maintain a constant ring thickness even as the diameter of the tree increases, but inexorably the increasing diameter (and in a sense height) of the bole causes a reduction in ring width even if volume growth rate is maintained. As competition and climate factors are encountered over the life span of the tree, the thickness of the ring must decline. These relationships must be accounted for in the analysis of rings between and within trees. The problems with dendrological studies, which the forester Pearson hinted at in this contribution, continue to bother many silviculturists and quantitative foresters to this day. Of course, volume increment is much more difficult to obtain than ring-width.

The methods for studying growth and yield have continued to be based primarily on long-term remeasured permanent plots. The value of these plots to growth and yield and to future investigations of environmental change cannot be overestimated. Short term plots may be useful for interim analyses, and may contribute to a data base which consists primarily of long term plots, but they do not of themselves constitute a source worthy of estimating the growth of forest stands. Stem analyses have contributed significantly to our understanding of forest growth and continue to have a role to play, but neither can they be the sole information on stand level growth. In like manner the tree-ring record of radial growth appears to have great potential for contribution to our understanding of growth and yield, but stand-dynamic considerations will probably always require some sort of permanent installation to evaluate growth in any quantitatively serious manner.

As has been noted, foresters interested in the results of stand management experiments did not become involved in dendro-ecological studies,

but the following exception provides a well-founded basis for future endeavors. The same year (1937) that Glock's book appeared, F. X. Schumacher and H. A. Meyer published *Effect of Climate on Timber-Growth Fluctuations*. Schumacher was one of the outstanding quantitative foresters to emerge early in the history of forestry in the United States. While the article seems to have failed to stimulate widespread use of the technique in similar treatment of growth and yield information then, the time may have arrived now for implementation of its inchoate substance. Schumacher and Meyer treated data brought from Switzerland by Meyer, regarding twelve white fir (*Abies alba*). They had the objectives to (1) partition the variation in annual growth over a 63-year period into within-stand and outside-stand influences and (2) to investigate the effects of climate on timber growth. While the species is foreign and the data over a half century old, I believe it could have relevance for current research in growth and yield for ponderosa.

The authors indicated that a measure of annual growth variation due to climate fluctuation is basic to judgements concerning the efficiency of silvicultural treatment in a regulated forest. Without information on the climate flux, comparison of periodic growth before and after silvicultural treatment may be seriously misleading.

Beginning with simple correlations between sample pairs of trees, which showed very little correlation, and proceeding to correlation between residuals for two groups of six trees that show very high correlations the authors indicate that factors external to the stand contribute the bulk of the variation between the averages of the six trees. The principal factors were most likely weather or climate. Analysis of variance of the same cores indicate that climate accounted for about 93 percent of the variation external to the individual trees. The amount of growth variation decreases with period length, but the differences are notable for periods commonly used to remeasure permanent sample plots. Table 4 from Schumacher shows the percent coefficient of variation for diameter growth. Treatments which have effects similar in magnitude to the remaining variation would be extremely difficult to demonstrate.

Having identified the culprit in the tree-ring record as climate, Schumacher and Meyer made an effort to establish a method for accounting for

the climatic fluctuations when making comparisons of periodic increment. I will not try to cover their results here, partly because I believe newer analysis methods are more appropriate today, but I suggest that interested researchers should consult the original.

Their conclusions need reiteration. Most of our knowledge of growth and yield comes in the form of information from periodic remeasurement of sample plots. Comparisons among treatments for

Table 4. -- Coefficient of variation of periodic diameter growth.
(from Schumacher and Meyer (1937))

Period	Deviation from 63-year trend	
	1-std dev	3-std dev
1	15.4	46
5	6.9	21
10	4.9	15
15	4.1	12
20	3.4	10

the purpose of estimating the effect on growth of an applied treatment or an observed catastrophic event is the common method of identifying potential treatments or causes of unusual events or trends.

The antecedent analyses illustrate clearly that climate fluctuations from year to year affect increment to an extent that might mask or enhance the effect we are investigating in a particular growth period. A method to eliminate the effect of climatic change may be necessary in order to obtain an estimate of the effect that is actually due to the treatment or observed event.

THE KALMAN FILTER FOR TIME VARYING PARAMETERS

Tree-ring analyses began with assumptions that related strongly to the arid southwest. As I have noted some of the assumptions were objectionable to foresters involved in growth and yield because foresters tend to see that individual tree growth changes systematically with stand dynamics regardless of short term climate changes.

P. C. Van deusen and J. Koretz (1988) and Van Deusen (Dynaclim version 2.0, 1989) present a series of tree-ring analysis programs which have rather distinctive properties: 1) there is no requirement for the uniformitarian assumption, 2) all trees are maintained in the chronology as opposed to a single index series; data reduction is obtained by estimating parameters rather than a single mean, and 3) simultaneous estimation of mean and climate model is achieved eliminating the necessity of subjectively fitting a pre-whitening curve.

A state space formulation is developed in Van Deusen and Koretz. The equation of observations is:

$$Y_t = F_t a_t + v_t \quad (1)$$

where Y represents ringwidths, F is a matrix of 1's in column one and 0's elsewhere, a represents the parameter vector to be estimated, v is the error vector and subscript t indicates the number

of time intervals in the chronology. The transition equation is given by:

$$a_t = G_t a_{t-1} + w_t \quad (2)$$

where G is a transition matrix and w is the associated error vector. For both error vectors, error matrices (V_t and W_t) exist and can be specified.

These equations can be solved using Kalman filter theory. The Kalman filter is a set of equations that provide estimates of the parameters in equations 1 and 2 that have the general property of being the best linear unbiased estimates when certain assumptions about the error matrices V_t and W_t hold. The error matrices both have mean zero, but are not contemporaneously correlated. Further there should be no serial correlation within or between the two error matrices.

State parameters are estimated in three steps: prediction, update and smoothing equations. The process is complicated, but the idea is relatively simple. The Kalman filter has been around for many years in the electronics industry as a method for removing noise from electronic signals that may be modulated, i.e., deteriorating over time.

The programs developed in DYNACLIM (Van Deusen 1989) allow for the dynamic modeling of climate from tree rings that have statistically sophisticated properties when compared to the more subjective methods that have developed over the years. The comparison of this method with older methods has proven quite favorable. Illustration of the results of sample analyses are presented, briefly. Figure 1 shows the time varying parameter for a Michigan/hemlock series. Figure 2 portrays the actual ring variation for a number of red spruce from White Face Mountain. This new analysis system provides us with a more objective methodology that also appears to have the potential to answer some of the traditional forester's objections to dendro-ecological investigations.

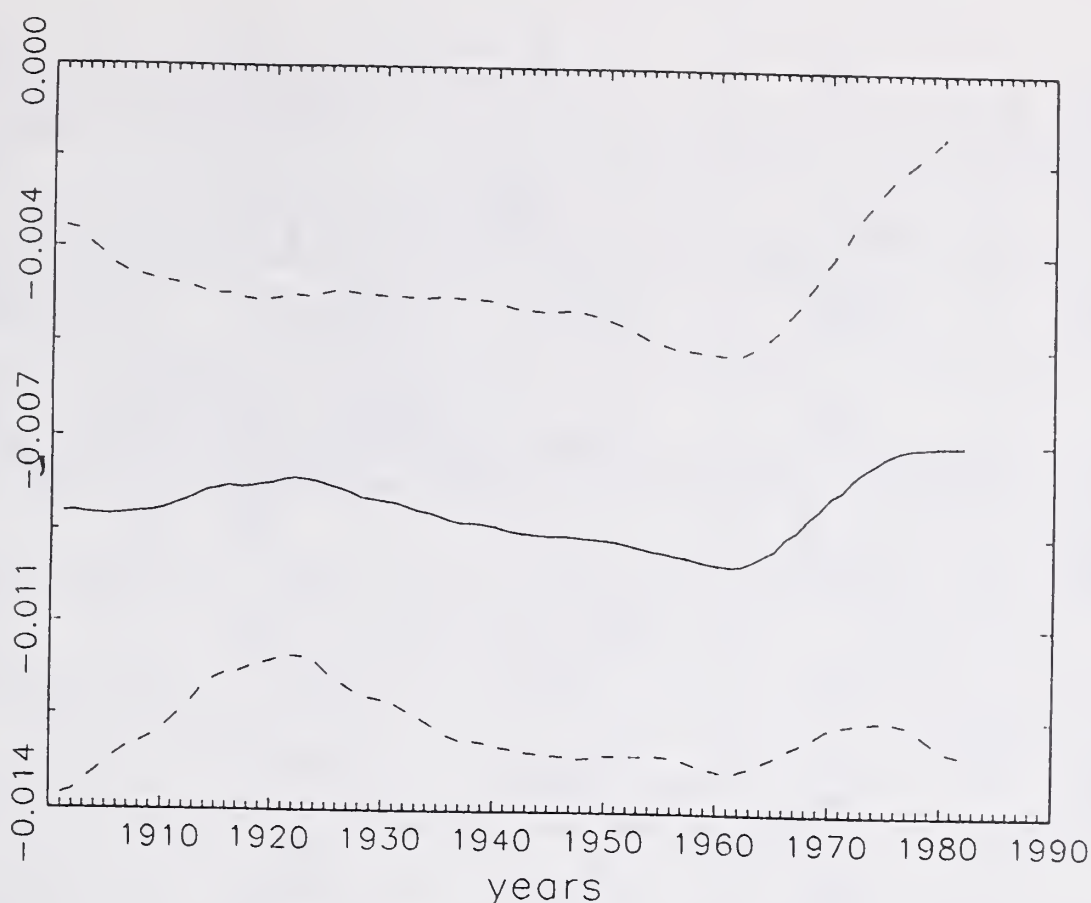


Figure 1.-- Example graph made with Dynaclip module dynaplot, showing time varying parameter and approximate 95% confidence intervals for the parameter. (from Dynaclip version 2.0, Van Deusen 1989)

SUGGESTIONS AND CONCLUSIONS

Foremost among considerations for growth and yield in the management of any forest type must be a serious commitment to long-term permanent plot studies. No serious forest growth program can be conducted with temporary plots alone.

Dendro-ecological methods can contribute in several ways to the utility of permanent plots. First, the effect of random temporal correlation between short term climate fluctuation and treatment (or observed condition class) can be reduced, greatly enhancing the scientific and predictive value of permanent plots. Second, the results from permanent plots may be extrapolated to conditions not encountered in the permanent plot installation with somewhat more confidence, if a solution to the forester's objections can be found.

This leads to my conclusions which are highly speculative, but I hope constructive in the long run. First, the management of all forest types is increasingly dependent on long-term accurate appraisals of the growth rates in a changing environment. Changes in the atmospheric environment could have major impact on the growth or health of forests, however, we will never be able to speak knowledgeably about current growth declines if we cannot determine long-term trends. It is unlikely that detailed growth and yield programs such as are being developed for rapidly

growing Southern forest tree species types or Pacific Northwest types will ever be constructed for slower growing ponderosa pine type forests. Dendro-ecology in conjunction with existing permanent plot installations may provide a workable growth estimation approach. As we reflect on Schumacher and Meyer's paper, we ought to see that changes in short term climate patterns should not have been ignored by foresters for the past 50 years. Periodic remeasurements should have been corrected for climatic effects as they suggested. Second, foresters shouldn't turn up their noses at the serious contributions that dendrochronologists have made to understanding climate. If there are legitimate forestry condemnations of dendro-ecology, they lie in the inability to reconstruct the mortality of the stand. But perhaps we have simply overlooked some possibilities due to the NIH³ objection. It is true, dendrochronologists have concentrated on extracting the climate signal by extracting cores from dominant trees. However, it is possible that a stand dynamic signal remains in the tree-ring record in intermediate or suppressed trees. It is likely that the signal would be difficult to extract, but we have new statistical tools with which to examine the records.

³ Not invented here, NIH.

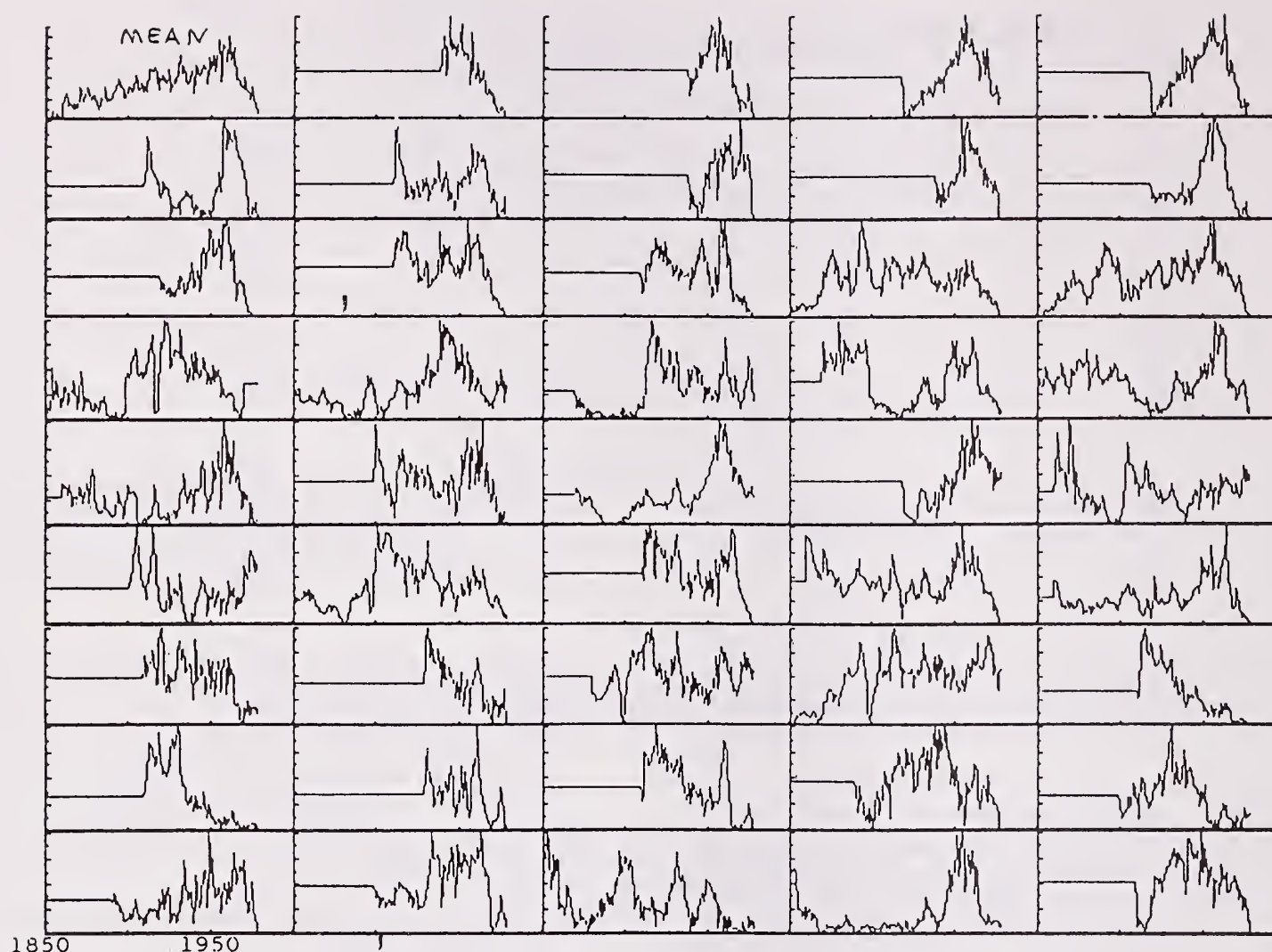


Figure 2.-- Mean tree-ring chronology and 44 individual tree cores from Whiteface Mountain red spruce. Plots extracted from program multiplot of Dynacliim version 2.0 (Van Deusen 1989)

It is up to us now; we need to assemble the tools to study growth in our changing environment, if we hope to explain observed variation in tree growth (health). We will need to use all the knowledge and resources available to us. At a minimum, this means continuing to study periodic growth from permanent plots, supplementing this information with tree-ring record analyses to determine the historical trends and possible shifts in environmental conditions, and applying the latest statistical analysis techniques to detect and identify environmental signals in the development of trees and forest stands.

LITERATURE CITED

- Miller, P. R., T. C. Quick, P. L. Vincent, R. E. Van Doren, and M. A. Thomas. 1978. Relationships of cumulative transpiration and oxidant dose to foliage injury development of ponderosa and Jeffrey pines. *Phyto. News* 12(9) 153.
- Böhm, M. 1989. A regional characterization of air quality and deposition in the coniferous forests of the western United States. IN: Olson and Lefohn, (Eds) *Transactions --The Effects of Air Pollution on Western Forests*, Air and Waste Management Assoc. Anaheim, CA 29-30 June 1989.
- Fritts, H. C. 1976. *Tree Rings and Climate*. Academic Press. New York.
- Glock, W. S. 1937. *Principles and Methods of Tree-Ring Analysis*. Carnegie Institution. Washington, DC.
- Graybill, D. A. and M. R. Rose. 1989. Analysis of growth trends and variation in conifers from Arizona and New Mexico. IN: Olson and Lefohn, (Eds) *Transactions --The Effects of Air Pollution on Western Forests*, Air and Waste Management Assoc. Anaheim, CA 29-30 June 1989.
- Pearson, G. A. 1950. *Management of ponderosa pine in the southwest*. USDA Forest Service, Agricultural Monograph No. 6.

Schumacher, F. X. and H. A. Meyer. 1937. Effect of
Climate on Timber-growth Fluctuations.
Journal of Agricultural Research Vol 54 No.
2. Washington DC. p 79-107.

Van Deusen, P. C. and J. Koretz. 1988. Theory and
programs for dynamic modeling of tree rings
from climate. GTR SO-70. USDA Forest
Service, Southern Forest Exp. Stn., New
Orleans, LA. 18 p.

Van Deusen, P. C. 1989. DYNACLIM, version 2.0.
(available from the author), Institute for
Quantitative Studies, Southern Forest Exp.
Stn, USDA Forest Service, New Orleans, LA.

A Growth and Yield Parameter Recovery Model for *Pinus cooperii* in Northern Mexico¹

Celedonio Aguirre Bravo and Susan Winter²

Abstract.— Stand stock tables are estimated for a species closely related genetically and ecologically to *Pinus ponderosa* using a parameter recovery model to describe the product size class information of the stand. The diameter distributions predicted with the Weibull parameter recovery model are validated with an independent set of data using the Chi-square and Kolmogorov-Smirnov goodness of fit statistics as criteria for comparison. The observed diameter distributions of the validation data were closely approximated with the parameter recovery procedure used in this study.

INTRODUCTION

Stand average and diameter distribution models are the two most common approaches for predicting the growth and yield of forest stands. Stand average models have limited value to forest managers because they do not produce detailed information of the product class size distribution for a particular set of stand conditions. Diameter distribution models, on the other hand, provide a full description of the stand structure in terms of number of trees, mean height, basal area, and volume by diameter class. Models for predicting detailed information about the stand structure are essential to forest management planning.

Different mathematical functions have been used to model diameter distributions in even-aged stands. Evaluation of these probability density functions (pdf) indicate that they differ in flexibility and complexity when fit to diameter distributions (Lenhart 1968), and their cumulative density functions (cdf) may or may not have a closed form solution (Hafley and Schreuder 1977, and Cao 1981). For example, the beta distribution is flexible enough to model diameter

distributions, but its cdf does not exist in closed form (Burkhardt and Strub 1974). In this case, numerical integration techniques are required in order to determine the proportion of trees in each diameter class.

The Weibull distribution possesses many desirable properties for fitting diameter distributions. Its genesis, properties and applications are described by Johnson and Kotz (1980). An important advantage over the beta distribution is that its cdf has a closed form and is more flexible for modelling diameter distributions of different shapes (Bailey and Dell 1973, Frazier 1981, Clutter et al. 1983). The Johnson's SB distribution (Johnson 1949) has been found to be consistently better than the Weibull. However, in addition to the lack of a closed form expression for its cdf, the use of this function is more complex and involves the prediction of four parameters (Rennolls et al. 1985). The Weibull pdf exists in either a two or three parameter form. The three parameter form has the advantage of providing more flexibility for modelling diameter distributions (Knoebel 1986).

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² Celedonio Aguirre Bravo is Professor of Forest Management at the Universidad Autonoma Chapingo, Division de Ciencias Forestales, Texcoco, Mexico. Susan A. Winter is Professor of Forest Management and Economics, Programa Forestal, Colegio de Postgraduados, Chapingo, Mexico.

Diameter distribution models based on the Weibull distribution require efficient procedures to determine the parameter estimates of its probability density function. A common approach consists of estimating the Weibull parameters as a function of some average stand attributes (i.e., stand age, site index, and stand density). Other techniques predict the 24th, 63rd, and 93rd percentiles of the weibull pdf from stand average attributes in order to solve for the parameter estimates (Clutter et al. 1983). These methods may result in biased parameter estimates due to the

low R^2 of the parameter prediction equations (Frazier 1981, Bailey et al. 1981).

Another alternative used to obtain estimates of the parameters of the Weibull pdf is based on the parameter recovery procedure introduced by Hyink (1980). The method consists of estimating the first two noncentral moments of the Weibull pdf from stand average models in order to solve for the parameter estimates. The advantages of this approach are the ability to partition yield by diameter class, mathematical compatibility between stand average models and diameter distribution models, and consistency among the various stand yield estimates (Knoebel 1986). A generalized framework of this technique is given by Hyink and Moser (1983).

The purpose of this study was to develop a parameter recovery growth and yield-based model using temporary plot data from natural even-aged stands of *Pinus cooperii* (Blanco) from Durango State, Mexico. The parameter recovery procedure of the model is based on the technique described by Burk and Burkhart (1984). An evaluation of the model's accuracy and ability to recover stand diameter distributions was conducted using an independent set of validation data.

DATA

Data for this study were collected from natural even-aged stands of *Pinus cooperii* at the El Salto Forest Management Unit No. 6 Durango State, Mexico. A sample of 1850 temporary plots of 0.0125 ha were surveyed from 800 stands of a wide range of ages, site indices, and stand density. Plots in each stand were measured for the following information: DBH (cm), tree height (TH; m), 5 and 10-year diameter increment (mm) of dominant - codominant trees, age of dominant and codominant trees (years), crown class dominance, bark thickness (mm), and species. Trees in each plot were tallied to a 2.5 cm DBH limit. Plots having a species mixture higher than 5% were not considered in this study.

Plot data were summarized to generate the following variables on per hectare basis: mean age (A), mean dominant-codominant height (H), mean height per diameter class (HM), quadratic mean diameter (Dq), arithmetic mean diameter (D), minimum observed DBH, current basal area (B), five-year period basal area growth, volume (V), and Reineke (1933) stand density index (SDI). Plots for all these variables indicated a reasonable distribution over a wide range of ages, site indices, and stand densities.

From this data set, a random sample of 70 plots from stands of different ages, site indices, and stand densities was used to validate the performance of the parameter recovery procedure. The remaining plots were utilized for developing growth and yield equations.

PARAMETER RECOVERY PROCEDURE

The three parameter Weibull probability density function (pdf) was used for modelling the diameter distribution of natural even-aged stands of *Pinus cooperii*. The pdf of the Weibull is given by

$$(1) \quad f(x; a, b, c) = (c/b) * [(x-a/b)^{c-1}] * \{ \exp[-(x-a/b)^c] \}$$

$$a \leq 0$$

$$b, c > 0$$

$$a < x < \alpha$$

$$0, \text{ otherwise}$$

where

a = location parameter
b = scale parameter
c = shape parameter
x = dbh

Parameter estimates of this pdf are determined using the parameter recovery procedure introduced by Hyink (1980). A theoretical discussion of this procedure to diameter distribution modelling is given by Frazier (1981), Matney and Sullivan (1982), Cao et al. (1982), and Hyink and Moser (1983). The parameter recovery system is based on the method of moments technique of pdf parameter estimation as discussed by Mendenhall and Schemper (1983). For a diameter distribution, the first and second moments about the origin are given by

$$(2) \quad E(x) = x_i / N = \bar{x} = D$$

$$(3) \quad E(x^2) = x_i^2 / N = B / 0.00007854N = \overline{x^2}$$

where

\bar{x} = the arithmetic mean diameter of the stand (D)
 $\overline{x^2}$ = the quadratic mean diameter of the stand
N = stems per hectare
B = basal area per hectare

Stand average estimates of D, B, and N, for the first and second noncentral moments of the Weibull pdf, were determined with the following equations:

$$(4) \quad D = \exp[-0.455 + 0.254 \ln(H) + 0.7631 \ln(A) + 0.03195 \ln(B)]$$

$$R^2 = 0.45 \quad \text{MSE} = 0.35$$

$$(5) \quad B = \exp[-3.347 + 0.003069(A) + 0.99259 \ln(SDI) + 0.13046 \ln(H) - 4.31(1/A)]$$

$$R^2 = 0.97 \quad \text{MSE} = 3.25$$

$$(6) N = \exp[7.3599 - 0.02471(A) + 0.8228$$

$$\ln(B) - 1.022 \ln(H) + 0.18025(B/A)]$$

$$R^2 = 0.88 \quad \text{MSE} = 25.8$$

Estimates of B at several projection ages were determined with the following equation:

$$(7) B = \exp\{(A_i/A_{i+1}) \ln(B_i) + (A_i/A_{i+1})$$

$$+ 0.04919[1 - (A_i/A_{i+1})]S\}$$

$$R^2 = 0.97 \quad \text{MSE} = 4.75$$

where

A_i = current stand age
 A_{i+1} = projected stand age
 B_i = current basal area
 B_{i+1} = projected basal area
 S = site index

The system of equations to solve for the parameter estimates of the Weibull pdf is

$$(8) \bar{x} = \int_0^{\alpha} x f(x; b, c) dx = a + b\Gamma(1+1/c)$$

and

$$(9) \overline{x^2} = \int_0^{\alpha} x^2 f(x; b, c) dx = a + b^2\Gamma(1+2/c)$$

The estimated variance (s^2) and coefficient of variation (CV) of the distribution are given by

$$(10) s^2 = [\overline{x^2} - \bar{x}^2] = b^2 [\Gamma(1+2/c) - \Gamma^2(1+1/c)]$$

$$(11) CV = (s/\bar{x}) = \frac{[\Gamma(1+2/c) - \Gamma^2(1+1/c)]^{1/2}}{\Gamma(1+1/c)}$$

where

Γ = the gamma function.

The location parameter (a) of the Weibull pdf is predicted outside the system of equations to avoid convergence problems during the process of parameter estimation (Cao and Burkhart 1984, Knoebel et al. 1986). Parameter (a) is considered to be the smallest possible diameter in the stand (Bailey and Dell 1973, Rennolls et al. 1985). Given stand average estimates of \bar{x} and $\overline{x^2}$, there exists a unique solution for c in equation (11), and the value of this parameter can be obtained using iterative techniques. Equation (8) can be solved for b given that c is known, and the value for the location parameter (a) is a constant estimated as follows

$$(12) a = \min(\text{DBH}) = \max[0.5932 -$$

$$0.16567(B) + 0.95998(Dq)]$$

$$R^2 = 0.89 \quad \text{MSE} = 0.85$$

Given initial conditions of stand age, dominant height, and basal area, the prediction of $\min(\text{DBH})$, D, and Dq is necessary for solving the moment-based three parameter system of equations. A computer solution routine developed by Burk and Burkhart (1984) was used to solve for the Weibull parameter estimates. The program is based on a set of iterative routines which uses a combination of the bisection and secant methods for finding roots of nonlinear equations (Devroye 1986). These routines are used to provide a solution of $f(x; \theta)$ in order to recover the diameter distribution of the stand.

Total per unit area values of the stand attribute Y can be obtained for a given solution of $f(x; \theta)$. That is

$$(13) Y = [N \int_{x_1}^{x_2} f(x; \theta) dx] g_i(x)$$

where

$f(x; \theta)$ = the Weibull pdf for x
 $g_i(x)$ = stand attribute as a function of x
 x_1 and x_2 = lower and upper diameter limits for the product described by $g_i(x)$

The probability that x lies in the diameter class (x_1, x_2) is found by integrating the probability density function $f(x; \theta)$ between the limits x_1 and x_2 . That is

$$(14) \text{Prob}(x_1 < x_2) = \int_{x_1}^{x_2} f(x; \theta) dx = \{\exp[-x_2^{-a/b}] - \exp[-x_1^{-a/b}]\}^c$$

Tree-Level Equations

Diameter distribution growth and yield models require an estimate of mean tree height in each diameter class in order to determine the mean tree volume of each class. Several techniques have been proposed (Lenhart and Clutter 1971, Matney and Sullivan 1982). In this study, the mean tree height (HM) in each diameter class (DC) of each plot was first determined. The resulting HM observations of 1750 plots were then fit to develop the following equation:

$$(15) HM = \exp[-0.1985 + 0.2258 \ln(D) - 0.00987 \ln(B) - 1.3791(1/A) + 0.8152 \ln(H)]$$

$$R^2 = 0.93 \quad \text{MSE} = 2.25$$

A similar technique developed by Burk and Burkhart (1984) was used to predict the probability (P) that a tree is of sawtimber quality. The product class information of each tree for all the plots

of this study was assessed using a nonlinear taper equation for this species. To qualify as sawtimber, trees met the following criteria: length of first log larger than 6m, and a top diameter of that log larger than 25cm. The model to estimate P was as follows:

$$(16) P = \{1.0/[1.0+\exp(11.6598-0.030327(DBH) - 0.14317(TH))]\}$$

$$R^2 = 0.85 \quad MSE = 0.013$$

Equations for predicting site index, stem taper, stem volume, and commercial volume to a diameter limit were developed as a part of this study.

COMPUTER PROGRAM

The computer program consists of stand average and tree-level equations and of a computer solution routine to solve for the Weibull parameter estimates. Given initial stand conditions for stand age, dominant height, and basal area, the program computes the stand site index, stem per hectare, stand density index, quadratic mean diameter, arithmetic mean diameter, and the Weibull parameter estimates. For the same initial conditions, the program also produces the corresponding stand-stock table. Once the stand-stock table is displayed, the user has the option of projecting the stand conditions into the future or terminating the program (figure 1). Source code for the computer program is available from the authors.

Given a solution for $f(x;\theta)$, the proportion of the total number of trees (p_i) in a diameter class (w_i) was determined as follows:

$$p_i = \int_{x_1}^{x_2} f(x;\theta)$$

and the number of trees (n) in the diameter class w_i was computed as $n = p_i * N$. Equations to predict tree height, tree basal area, total and commercial tree volume, and the probability of sawtimber were then used to calculate the $g(x)$ stand attributes in the stand-stock table. Midpoint DBH's were used to compute class basal area, mean tree height, and volumes. This procedure may result in some small bias in the estimation of basal area and volume in each diameter class. The magnitude of this bias, however, is not significant for practical purposes. Numerical integration techniques can be used to reduce the bias which results from using midpoint diameter classes (Hafley et al. 1982).

A sensitivity analysis of the parameter recovery model was conducted to analyze its behavior with respect to changes in stand age, site index, and stand density. For a random sample of 250 plots from the 1850 temporary plots, the algorithm to solve for the Weibull parameter estimates converged on all plots used for this analysis. Stand average equations used to compute

the first and second moments of the Weibull distribution performed quite well for estimating the parameter estimates. Diameter distributions estimated for a wide range of stand conditions showed that the frequency of trees in each diameter class decreases as the stand age increases (figure 2). The number of diameter

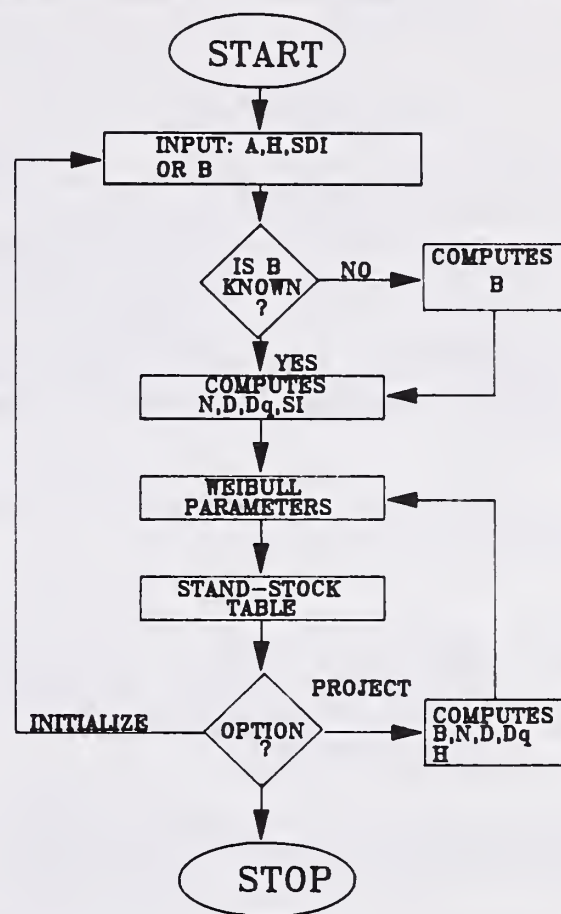


Figure 1.— Flow diagram to compute stand-stock tables using the Weibull parameter recovery model.

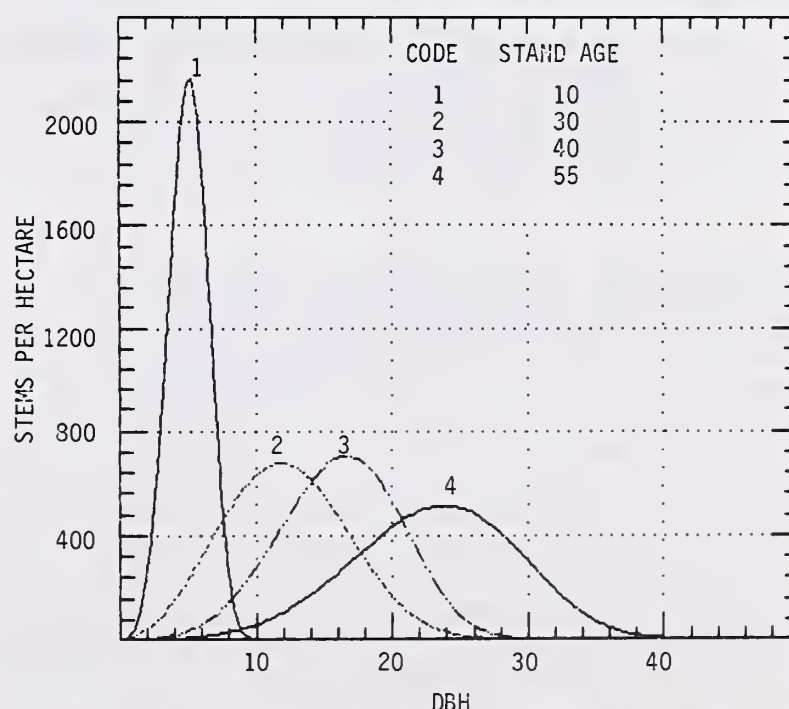


Figure 2.— Diameter distributions at several projection ages estimated with the Weibull parameter recovery model.

classes and trees in each diameter class, as well as the degree of skewness of the diameter distribution increases at higher site indices and stand basal areas. Merchantable volume increases with age and site index, and decreases if the stand is developing at higher stand densities. Stand-stock tables generated with this model are presented in Appendix 1.

MODEL VALIDATION

The performance of the model for recovering the parameter estimates of the diameter distribution were evaluated using an independent sample of validation data. Three statistical tests were used: Kolmogorov-Smirnov goodness of fit, Chi-square goodness of fit, and the sign test. The Kolmogorov-Smirnov statistic (K-S) compares the observed and the recovered distributions (Massey 1951). That is,

$$k = \max \left| F_0(x) - S_n(x) \right|$$

where

$F_0(x)$ = hypothesized $f(x;\theta)$ obtained with the parameter recovery procedure

$S_n(x)$ = the observed distribution of the n trees on the plot.

Both distributions are significantly different if the computed value of k exceeds the critical value $k_\alpha(n)$. The Chi-square statistic is determined as follows:

$$\chi^2 = \sum \left[\frac{E_i - O_i}{E_i} \right]^2$$

where

E_i = the expected frequency of trees in the diameter class w_i

O_i = the observed frequency of trees in the diameter class w_i

z = the number of diameter classes w_i ($i=1, \dots, z$)

Larger values of the computed χ^2 statistic indicate that the recovered distribution is different than the observed distribution. The sign test is a nonparametric test for differences between paired observations of a sample. For this test, maximum likelihood Weibull parameter estimates for the validation plots were determined using the procedure developed by Zutter et al. (1982). These parameter estimates were then compared with the parameter estimates obtained with the parameter recovery procedure. The statistic of this test is $N(0,1)$ and is used to compare if the parameter estimates of both samples belong to the same population mean.

The goodness of fit tests indicated that most of the recovered diameter distributions were comparable to the diameter distributions of the validation data. Comparisons of K-S statistics

Table 1.— Results of the goodness of fit tests of comparing the recovered diameter distributions with the observed diameter distributions of the validation data.

Range of Age	Number of Plots	Trees per Plot	No. (%) Plots Rejected	
			χ^2	K-S
10-25	15	135	4(26.6)	3(20.0)
25-40	25	80	5(20.0)	4(16.0)
40-55	20	55	2(10.0)	3(15.0)
> 55	10	43	3(30.0)	2(20.0)

with the critical values ($k_\alpha(n)$) were not statistically significant in more than 75% of the plots for validation ($\alpha = 0.01$). Values for the K-S statistics tended to increase at younger (10 to 25 years) and older ages (> 55 years). Similar results were obtained using the Chi-square goodness of fit statistics (table 1). Both tests indicated that the diameter distributions were poorly recovered at stand ages greater than 55 years. Test statistics above this age might be biased due to the few diameter classes in each plot and the low frequency of trees in each diameter class.

Parameter estimates obtained with the parameter recovery model compared quite well with the maximum likelihood parameter estimates. Sign tests were statistically significant ($\alpha = 0.001$) for more than 90% of the validation plots. The recovered parameter estimates were positively biased. However, the amount of bias was insignificant for practical purposes. The location parameter exhibited more bias than the scale and range parameters. Bias in the location parameter is attributed to its procedure of estimation. Estimates of $\min(\text{DBH})$ are always greater than or equal to the true smallest diameter in the stand. The small bias of the scale and shape parameters might be related to the bias of the scale and shape parameter (Frazier 1981). In general, the validation results suggest that the recovered diameter distributions were no different from the observed distributions of the validation plots.

CONCLUSION

The parameter recovery technique used in this study provides a reliable description of the diameter distribution of natural even-aged stand of *Pinus cooperii*. Predictions and projections of the stand diameter structure were highly dependent upon the performance of equations to predict and project average stand attributes. Goodness of fit tests indicated that the model produced diameter distributions similar to observed distributions in the validation data. For the same data, the Weibull parameter estimates obtained with this model were statistically similar to the maximum likelihood estimates. Stand-tables generated with

this model provide detailed information about the stand structure for a wide range of ages, site qualities, and stand densities. It is suggested that the use of remeasured data from larger plots might significantly improve the efficiency of this technique for recovering diameter distributions.

LITERATURE CITED

- Bailey, R. L., and T. R. Dell. 1973. Quantifying diameter distributions with the Weibull function. *For. Sci.* 19:97-104.
- Bailey, R. L., et al. 1981. Diameter distribution models for repeatedly thinned slash pine plantations. In: *Proceedings First Biennial Southern Silvicultural Research Conference* (J. P. Barnett ed). USDA For. Service Tech. Rep. SO-34, 115-126.
- Burkhardt, H. E., and M. R. Strub. 1974. A model for simulation of planted loblolly pine stands. In: *Growth Models for Tree and Stand Simulation* (J. Fries, ed), p. 128-135. Royal Coll. For., Stockholm, Sweden.
- Burk, T. E., and H. E. Burkhardt. 1984. Diameter distributions and yields of natural stands of loblolly pine. VPI and SU, Sch. For. and Wildl. Resour. Publ. FWS-1-84, 46p.
- Cao, Q. V. 1981. Empirical diameter distributions and predicted yields of thinned loblolly pine plantations. Ph.D. Dissertation. VPI and SU. 102p.
- Cao, Q. V., and H. E. Burkhardt. 1984. A segmented distribution approach for modelling diameter frequency data. *For. Sci.* 30:129-137.
- Clutter, J. L., and F. A. Bennet. 1965. Diameter distributions in old-field slash pine plantations. *Ga. For. Res. Counc. Rep.* 13, 9p.
- Clutter, J. L., et al. 1983. *Timber Management: A Quantitative Approach*. John Wiley and Sons Press. 334p.
- Daniels, R. F., et al. 1979. Yield estimates for loblolly pine plantations. *J. For.* 77:581-586.
- Devroye, Luc. 1986. *Non-Uniform Random Variate Generation*. Springer-Verlag. 811p.
- Ford, E. D. 1975. Competition and stand structure in some even-aged plant monocultures. *J. Ecol.* 63:311-333.
- Frazier, J. R. 1981. Compatible whole-stand and diameter distribution models for loblolly pine plantations. Ph.D. Dissertation. VPI and SU. 130p.
- Hafley, W. L., and H. T. Schreuder. 1977. Statistical distributions for fitting diameter and height data in even-aged stands. *Can. J. of For. Res.* 7:481-487.
- Hafley, W. L., et al. 1982. A new yield prediction model for unthinned loblolly pine plantations. North Carolina State Univ., Sch. For. Res., South. For. Res. Cent., Bioecon. Modelling Proj., Tech. Rep. 1, 65p.
- Hyink, D. M. 1980. A technique for the recovery of stand structure from whole stand attributes. *Va. J. Sci.* 31:80 (Abstr.).
- Hyink, D. M., and J. W. Moser, Jr. 1983. A generalized framework for projecting forest yield and stand structure using diameter distributions. *For. Sci.* 29:85-95.
- Johnson, N. L. 1949. Systems of frequency curves generated by methods of translation. *Biometrika* 36:297-304.
- Johnson, N. L., and S. Kotz. 1970. *Continuous Univariate Distributions*. Houghton Mifflin Co., Boston.
- Kmenta, J. 1971. *Elements of Econometrics*. MacMillan Publishing Co., Inc. 655p.
- Knoebel, B. R., et al. 1986. A growth and yield model for thinned stands of yellow-poplar. Monograph no. 27. *For. Sci.* 62p.
- Lenhart, J. D. 1968. Yield of old field loblolly pine plantations in the Georgia Piedmont. Ph.D. Dissertation (unpublished). University of Georgia. 98p.
- Massey, F. J., Jr. 1951. The Kolmogorov-Smirnov test for goodness of fit. *JASA.* 46:68-78.
- Matney, T. G., and A. D. Sullivan. 1982. Compatible stand and stock tables for thinned and unthinned loblolly pine stands. *For. Sci.* 28:161-171.
- Mendenhall, W., and R. L. Scheaffer. 1973. *Mathematical Statistics with Applications*. Duxbury press. 561p.
- Rennolls, K., et al. 1985. Characterizing diameter distributions by the use of the Weibull distribution. *Forestry.* 58(1):57-66.
- Steel, R. G. D., and J. H. Torrie. 1980. *Principles and Procedures of Statistics: A Biometrical Approach*. 2nd edition. McGraw-Hill Book Company. 632p.
- Zutter, B. R., and R. G. Oderwald. 1981. The use of modified distributional techniques for quantifying forest populations. Unpublished report to the Forestry Sciences Laboratory, Southern For. Exp. Sta., Monticello, Arkansas, 4p.
- Zutter, B. R., et al. 1982. Weibull: A program to estimate parameters of forms of the Weibull distribution using complete, censored, and truncated data. Pub. No. FWS-3-82. Sch. For. and Wildl. Res. VPI.

APPENDIX 1

INITIAL CONDITIONS:

AGE: 40 Years
 SITE INDEX (Base 60): 25m
 BASAL AREA: 32m²
 TREES PER HECTARE: 560
 DOM./CODOM. HEIGHT : 19m
 ARITHMETIC MEAN DBH: 26.4cm
 QUADRATIC MEAN DBH: 27.2cm
 STAND DENSITY INDEX: 491
 WEIBULL PARAMETER EST.s:
 Location: 20.113
 Scale: 6.335
 Shape: 1.004

STAND/STOCK TABLE

DBH (cm)	TREES /HA.	Ba.AREA m ² /HA.	TOT. HEIGHT (m)	MERCH. VOL.(m ³) 10cm OB top	TOTAL STEM VOL .0cm OB top
20	175.2	5.5	17	0	49
25	210.5	10.3	18	16	96
30	95.6	6.8	18	33	65
35	43.2	4.2	19	35	42
40	19.5	2.5	20	24	25
45	8.8	1.4	21	15	15
50	4.0	.8	21	8	8
55	1.8	.4	21	5	5
60	.8	.2	21	3	3
65	.4	.1	22	1	1
70	.2	.1	22	1	1
75	.1	.0	23	0	0
<hr/>					
TOTAL	559.9	32.2	----	141	311

PROJECTED CONDITIONS:

AGE: 45 Years
 SITE INDEX (Base 60): 25m
 BASAL AREA: 36m²
 TREES PER HECTARE: 529
 DOM./CODOM. HEIGHT : 20m
 ARITHMETIC MEAN DBH: 28.7cm
 QUADRATIC MEAN DBH: 29.5cm
 STAND DENSITY INDEX: 691
 WEIBULL PARAMETER EST.s:
 Location: 21.765
 Scale: 6.968
 Shape: 1.003

STAND/STOCK TABLE

DBH (cm)	TREES /HA.	Ba.AREA m ² /HA.	TOT. HEIGHT (m)	MERCH. VOL.(m ³) 10cm OB top	TOTAL STEM VOL .0cm OB top
20	52.6	1.7	18	0	15
25	243.9	12.0	18	22	117
30	119.3	8.4	19	46	86
35	58.1	5.6	20	50	59
40	28.3	3.6	21	37	38
45	13.7	2.2	21	24	24
50	6.7	1.3	22	15	15
55	3.2	.8	22	9	9
60	1.6	.4	23	5	5
65	.8	.3	23	3	3
70	.4	.1	23	2	2
75	.2	.1	24	1	1
80	.1	.0	24	1	1
<hr/>					
TOTAL	528.7	36.4	----	215	375

PROJECTED CONDITIONS:

AGE: 50 Years
 SITE INDEX (Base 60): 25m
 BASAL AREA: 40m²
 TREES PER HECTARE: 461
 DOM./CODOM. HEIGHT : 22m
 ARITHMETIC MEAN DBH: 32.2cm
 QUADRATIC MEAN DBH: 33.1cm
 STAND DENSITY INDEX: 722
 WEIBULL PARAMETER EST.s:
 Location: 24.588
 Scale: 7.599
 Shape: 1.001

STAND/STOCK TABLE

DBH (cm)	TREES /HA.	Ba.AREA m ² /HA.	TOT. HEIGHT (m)	MERCH. VOL.(m ³) 10cm OB top	TOTAL STEM VOL .0cm OB top
25	146.6	7.2	20	16	75
30	151.7	10.7	21	69	117
35	78.6	7.6	21	74	85
40	40.7	5.1	22	57	59
45	21.0	3.3	23	39	40
50	10.9	2.1	23	26	26
55	5.6	1.3	24	17	17
60	2.9	.8	24	10	10
65	1.5	.5	25	6	6
70	.8	.3	25	4	4
75	.4	.2	25	2	2
80	.2	.1	26	1	1
85	.1	.1	26	1	1
90	.1	.0	26	0	0
<hr/>					
TOTAL	461.1	39.4	----	325	445

PROJECTED CONDITIONS:

AGE: 55 Years
 SITE INDEX (Base 60): 25m
 BASAL AREA: 43m²
 TREES PER HECTARE: 403
 DOM./CODOM. HEIGHT : 24m
 ARITHMETIC MEAN DBH: 35.8cm
 QUADRATIC MEAN DBH: 36.7cm
 STAND DENSITY INDEX: 744
 WEIBULL PARAMETER EST.s:
 Location: 27.559
 Scale: 8.207
 Shape: 1.005

STAND/STOCK TABLE

DBH (cm)	TREES /HA.	Ba.AREA m ² /HA.	TOT. HEIGHT (m)	MERCH. VOL.(m ³) 10cm OB top	TOTAL STEM VOL .0cm OB top
30	181.9	12.9	22	93	148
35	101.1	9.7	23	103	116
40	54.9	6.9	23	82	85
45	29.8	4.7	24	59	60
50	16.1	3.2	24	41	41
55	8.7	2.1	25	27	27
60	4.7	1.3	26	18	18
65	2.6	.8	26	12	12
70	1.4	.5	26	7	7
75	.7	.3	27	5	5
80	.4	.2	27	3	3
85	.2	.1	28	2	2
90	.1	.1	28	1	1
95	.1	.0	28	1	1
TOTAL 402.8		43.0	----	453	524

PROJECTED CONDITIONS:

AGE: 60 Years
 SITE INDEX (Base 60): 25m
 BASAL AREA: 45m²
 TREES PER HECTARE: 353
 DOM./CODOM. HEIGHT : 25m
 ARITHMETIC MEAN DBH: 39.4cm
 QUADRATIC MEAN DBH: 40.4cm
 STAND DENSITY INDEX: 761
 WEIBULL PARAMETER EST.s:
 Location: 30.686
 Scale: 8.767
 Shape: 1.006

STAND/STOCK TABLE

DBH (cm)	TREES /HA.	Ba.AREA m ² /HA.	TOT. HEIGHT (m)	MERCH. VOL.(m ³) 10cm OB top	TOTAL STEM VOL .0cm OB top
30	65.4	4.6	23	37	56
35	125.0	12.0	24	135	150
40	70.9	8.9	24	111	114
45	40.0	6.4	25	83	84
50	22.5	4.4	26	59	60
55	12.7	3.0	26	41	41
60	7.1	2.0	27	28	28
65	4.0	1.3	27	19	19
70	2.2	.9	28	13	13
75	1.3	.6	28	8	8
80	.7	.4	28	5	5
85	.4	.2	29	3	3
90	.2	.1	29	2	2
95	.1	.1	30	1	1
100	.1	.1	30	1	1
TOTAL 352.7		45.0	----	548	585

Factors Affecting Ponderosa Pine Forest Resource Outputs: Moderator's Comments

**Michael R. Wagner
NAU School of Forestry**

The multiresource management of the public forests of the U.S. is mandated by federal legislation directing land management agencies to consider all resource outputs in their management decisions. Many factors including political constraints, paucity of site specific ecological data, and shortage of decision support methodology currently limit the implementation of multiresource management. This section of the conference proceedings focuses on some of the ecological factors that limit the accomplishment of multiresource goals and suggests some methodology for mitigating these factors.

Insects and diseases have been long recognized as important factors limiting the wood fiber production of forests. It is only recently that their effects on the other resource outputs such as recreation, aesthetics, water, grazing, and wildlife have been recognized. This historical precedence has led to a situation where methods are critically needed to assess the impacts of pests on these other mostly non-commodity outputs. While the long term solution will require considerable research effort, an interim qualitative technique, presented in this section, will permit the assessment of some of these factors. A second important reason why insects and disease effects have not been managed as effectively as possible relates to decision making processes. The successful management of pest species that affect multiresource outputs is dependent on integrating pest management into forest management through a process called integrated pest management (IPM). IPM has, to a large extent, not been practiced on public forest land. In this section a procedure for integrating pest management into forest management through the Integrated Resource Management (IRM) philosophy is presented. The IRM process in conjunction with an interdisciplinary approach is presented as the most expeditious

method to accomplish IPM and reduce the negative effect of pests on multiresource outputs.

Competing vegetation and site nutrient status are also factors that influence multiresource outputs. Political constraints have largely precluded the use of herbicides as a broad scale approach to managing competing vegetation. The use of livestock to achieve reduction in competing vegetation is an alternative method with considerable potential. Research results presented indicated that with careful management, collateral production of timber and livestock is feasible. Likewise, the careful management of fire can be an effective tool in achieving multiresource objectives. These objectives can only be achieved however, if careful attention is paid to factors such as season and intensity of fire. Research results are presented in this section that have implications for the appropriate use of prescribed fire to reduce fuels and improve site nutrient status.

Finally, the section concludes with a discussion of ponderosa pine tissue culture. The ever increasing demands on forests will likely justify the application of tree improvement methods. Many managers tend to view tree improvement methods such as genetic engineering and tissue culture as inconsistent with multiresource objectives. In reality, the methods can be used to enhance visual quality, biodiversity, wildlife habitat, etc., equally as well as enhancing fiber production. It is only the application of tissue culture methods, not the methods themselves, that limit their utilization.

Forest land managers will certainly need to consider and be aware of these and other factors that will ultimately limit the outputs of multiresource management of the ponderosa pine forest.

Assessing the Impacts of Foliage-Feeding Insects on Timber and Scenic Beauty of Ponderosa Pine: A Methodological Approach¹

Joel D. McMillin² and Michael R. Wagner³

Abstract.--In this paper we discuss impacts caused by insect defoliation on multiresource outputs (timber and scenic beauty) of ponderosa pine (*Pinus ponderosa* Dougl. ex Laws) forests. Hypothetical response functions for insect defoliation impacts on timber and scenic beauty resource outputs are proposed based on a review of the literature. For each functional relationship suggested, species dependent factors are determined and used to qualitatively assess the impact of foliage feeding. Selected insects are assigned quantitative ratings and ranked in high, moderate, and low impact categories. Implications of an insect's status as an economical or non-economical pest are discussed. The potential applications and limitations of this method to assess the impacts of insects on multiresource outputs are discussed.

INTRODUCTION

Today's forest may be thought of as a "multi-product factory"; with the forest manager trying to optimize all factory outputs. Commodities that are produced from an efficiently managed multi-resource forest include: timber products, range for livestock, recreation facilities including hunting and fishing, wildlife habitat, and water. Because forest planners feel pressure from special interest groups they need to manage forests economically while meeting the various and sometimes conflicting demands of the general public. Many factors influence the optimization of forest outputs; considering all of these factors is important to the efficiency of multiresource forestry.

One of these factors that has been widely studied is the impact of insects on forest outputs. The importance of forest insects range from beneficial impacts to extensive losses of timber production. Forest insects can adversely affect timber production, wood products, scenic beauty and recreational values by damaging the quality of timber, by causing delays in growth rates, or by thinning and discoloring of foliage. While tree killing by bark beetles and subsequent damage by wood boring insects may cause the most timber losses, certain defoliating insects also effect timber production and quality. Defoliators damage forests by consuming the foliage that produces photosynthate thereby reducing the growth rates of trees. But they can also kill vast stands of forest during population outbreaks.

Timber has historically been viewed as the major economic product of forests, consequently the focus of insect research has been on how insects affect timber production. Because of the wood products focus, there is relatively little literature on other impacts of insects (e.g. recreation, scenic beauty). In recent years there has been an increasing interest in non-timber resources values. Currently there is inadequate information on how specific insects may effect timber and non-timber resources simultaneously. For example, an insect species may have relatively little economical importance in terms of timber, but may cause significant

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²Joel McMillin is a Graduate Research Assistant in the School of Forestry, Northern Arizona University, Flagstaff, AZ

³Michael R. Wagner is an Associate Professor, School of Forestry, Northern Arizona University, Flagstaff, AZ

declines in recreation usage, or decreases in aesthetic value. Understanding how insects influence several multiresource outputs concurrently may aid the forest manager in optimizing all of the resource outputs. Thus, the need to systematically assess all resource impacts of insects and to develop some general hypotheses of how they effect non-timber resources is critical in managing today's forests.

In this paper we evaluate one section of the above mentioned need to analyze the impacts of insects on multiresource outputs. We concentrate on defoliating insects and their relative impacts on timber and scenic beauty of ponderosa pine (*Pinus ponderosa* Dougl. ex Laws) as a model for how multiresource impacts of insects can be assessed. We review pertinent literature in order to develop generalized response functions between insect-damaged foliage and impacts on timber and scenic beauty. Based on these functional relationships, factors determined to be species specific, or species dependent, are utilized to qualitatively assess the impact of foliage feeding insects. And in turn these insects are assigned quantitative ratings and ranked in impact intensity categories. The implications of an insect's status as an economical or non-economical pest in a broader multiresource category are then evaluated.

Impacts of Insects on Timber

Forest planners need to understand the impacts on tree growth rates by feeding insects if they are to accurately estimate multiresource outputs and/or decide to implement pest control practices. Damage to tree foliage causes disruptions in a variety of growth processes. For example, defoliation that results in a reduction of photosynthesis and a decrease in the production of carbohydrates may lead to a decline in growth hormones and other plant materials needed for cambial growth (Kozlowski 1971, Barbosa and Wagner 1989). Insect defoliators cause a wide variety of changes in the forest ranging from insignificant alterations, such as temporarily reduced growth in individual trees, to more economically important changes and impacts like severe growth loss, species composition changes in the forest stand, and complete stand mortality (Kozlowski 1971, Kulman 1971). There are several interrelated factors which influence the severity of impact on tree growth caused by defoliators. Factors known to influence the impact of defoliation include: preponderance for species outbreak (frequency and length of outbreak), degree or intensity of defoliation (amount of foliage removed), timing of defoliation (early season versus late season), and the age class of needle being damaged.

While growth reductions due to endemic populations are usually low or imperceptible, critical reductions or delays in growth occur during and following epidemics (outbreaks)

(Mattson and Addy 1975, Furniss and Carolin 1977). Insects vary in their frequency of population outbreaks. Some species may never reach epidemic levels, others only after long intervals of time, while a few frequently rise to large population numbers. During periods of sustained population outbreak, defoliators are able to destroy timber over large areas (Furniss and Carolin 1977). For example, *Neophasia menapia* (Felder and Felder) has had devastating impacts on timber production during outbreaks (Cole 1966), but these outbreaks have been infrequent. In contrast *Orgyia pseudotsugata* (McDunnough) has destroyed enormous areas of forest stands during outbreaks and these outbreaks occur frequently (Furniss and Carolin 1977).

Light defoliation for one or more years may cause little or no reduction in annual growth while heavy defoliation can result in severe growth reduction for several years or even mortality (Kulman 1971, Mattson and Addy 1975). In general, studies have shown that timber losses are proportional to the amount of foliage removed (Kulman 1971), however the losses are also closely related to the timing of defoliation and the age class of needles being damaged (Kozlowski 1971). Early season feeding is considered to be feeding that occurs on previous years' growth prior to needle expansion (pre-foliage flush). Early defoliation of ponderosa pine does not affect the flush of that season's foliage and damage is often confined to minimal reductions of growth rates. Defoliation of ponderosa pine current year needles later in the summer (post-foliage flush), occurs after the tree is capable of producing another needle flush. Therefore defoliation before foliage flush permits the pines to re-foliate, form buds for the next year, and recover before winter (Kozlowski 1971, Britton 1988). Thus insect feeding on ponderosa pine late in the growing season, at either low or high defoliation intensities, has a much more negative impact on timber production than early in the growing season (Figure 1).

Similarly, defoliation of old growth, or previous years' needles, (independent of the timing of defoliation) has relatively little effect on tree growth in comparison to defoliation of current-year foliage which generally causes more extreme growth reductions (Kulman 1965, Kozlowski 1971)(Figure 2). These differences in growth reductions are due to the higher photosynthetic efficiency of current-year needles (Kulman 1965).

Impacts of Insects on Scenic Beauty

The National Environment Policy Act of 1969 and the Multiple Use Sustained Yield Act of 1960 mandated forest managers to assess non-timber products in addition to timber products (Buhyoff and Leuschner 1978). Insect damage plays an important role in a forest manager's optimiza-

tion of these non-timber products of a multi-resource forest. Leuschner and Young (1978) found that southern pine beetle (*Dendroctonus frontalis* Zimm) caused greater economical damage to recreation sites than to timber. Thus, it is evident that the forest manager must consider to what degree insect-caused damage influences non-timber products, in order to truly assess all economic concerns. The non-timber product assessed in this paper is scenic beauty. Species specific factors which we believe influence the severity of defoliation impact on scenic beauty include: the nature of defoliation, distribution of feeding damage, and preponderance for species outbreak.

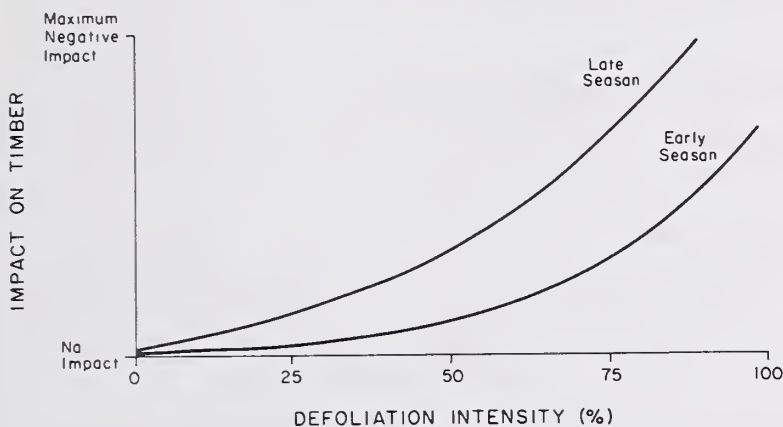


Figure 1.--Hypothetical response functions comparing early season (before natural foliage flush) and late season (post foliage flush) defoliation of current ponderosa pine foliage as they influence the relationship of defoliation intensity to resource impact.

A variety of feeding strategies are utilized by insects to attack pine needles. Feeding practices involve chewing, sucking, needle mining, and gall forming (Furniss and Carolin

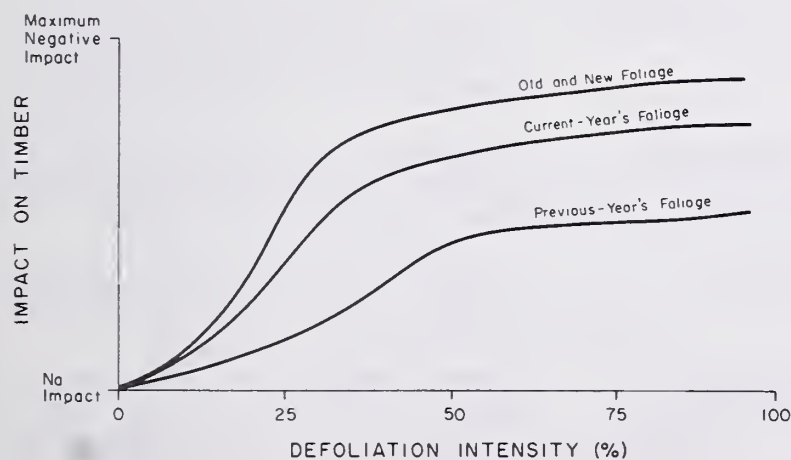


Figure 2.--Hypothetical response functions for timber impacts based on ponderosa pine defoliation intensity and foliage age class removed.

1977). The nature of feeding often determines if the foliage becomes discolored, dies prematurely, or is completely removed, and, in turn, influences the impact on scenic beauty. Discoloration of foliage due to insect feeding is noticed at low levels by the public (Buhyoff et al. 1982) and generally has a negative impact on scenic beauty (Buhyoff and Leuschner 1978) (Figure 3). Insects that do not cause visible color change, but which completely defoliate needles, may be less apparent (Krisko 1988).

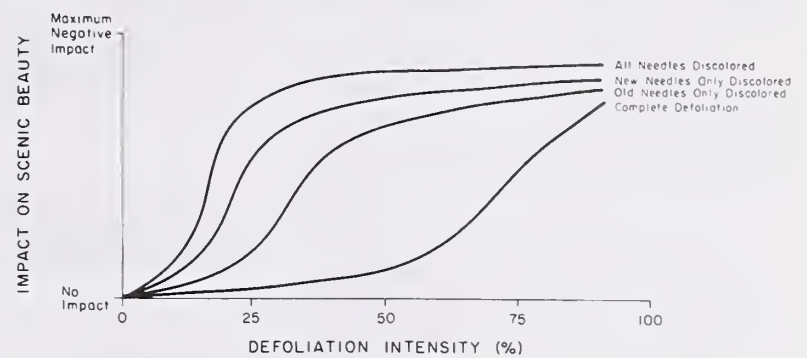


Figure 3.--Hypothetical response functions for the impact of defoliation intensity and foliage damage category on scenic beauty.

For example, defoliation by pandora moth (*Coloradia pandora* Blake) in Grand Canyon National Park was perceived by the public, but only at high levels (Krisko 1988).

The general public's perception of scenic quality may be influenced in part by the location in which they detect insect damage (Anderson 1981, Ribe 1989) (Figure 4). For example, low levels of defoliation and discoloration thinly scattered over a broad area may be "masked" or may even have a positive impact on scenic beauty when viewed from a roadside overlooking an expansive vista (Buhyoff and Leuschner 1978). The same level of defoliation

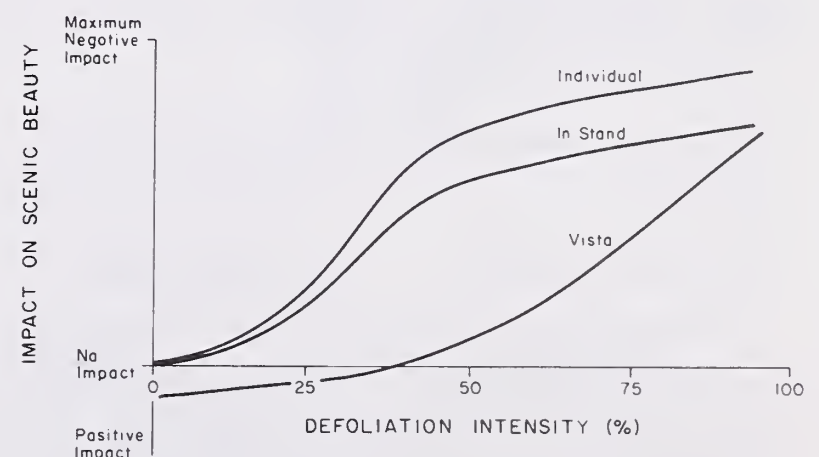


Figure 4.--Hypothetical response functions comparing perspective of view (individual tree, stand, and vista) as a relationship of defoliation intensity and scenic beauty.

and discoloration may have a negative impact on scenic beauty, however, when observed by a hiker trekking through a open forest stand.

As in insect impacts on timber, frequency and intensity of outbreak influences the degree of impact on scenic beauty. For example, although *Coleotechnites* spp have only moderate impacts on timber production due to its feeding on predominantly older needles (Stevens 1973, Stevens and Leatherman 1982), this species would have a relatively high negative impact on scenic beauty owing to its sustained population outbreak causing discoloration over large areas.

Important Defoliators of Ponderosa Pine

Furniss and Carolin (1977) list six orders and twenty-two families of insects known to damage ponderosa pine foliage. The orders with the most ponderosa pine defoliators are Lepidoptera, Hymenoptera, and Coleoptera; with the Lepidoptera order containing the most species generally considered to be destructive. Those species which exhibit low or no impacts on timber and scenic beauty were not included in our qualitative assessment, but they may be important species in influencing other multiresource outputs such as wildlife and recreation. Therefore, seventeen species out of fifty-four total species of defoliators or foliage-damaging insects were assessed (Table 1).

Table 1.--Ponderosa pine foliage feeding insects and the nature of their feeding damage.

Order/Family Feeding	Scientific Name	Common Name ¹	Nature of
Coleoptera:Chrysomelidae	<i>Glyptoscelis illustris</i>	leaf beetle	Adults feed on foliage during spring and summer.
Coleoptera:Scarabaeidae	<i>Phyllophaga falsa</i>	scarab beetle	Adults feed on foliage and may cause damage to seedlings in plantations.
Coleoptera:Curculionidae	<i>Cylindrocopturus eatoni</i>	pine reproduction weevil	Adults feed from June to August and may damage trees in plantations. Causes discoloration of foliage.
Coleoptera:Curculionidae	<i>Scythropus californicus</i>	elegant pine weevil	Adults feed on old foliage of young trees during spring and summer.
Lepidoptera:Tortriciidae	<i>Choristoneura lambertiana</i>	sugar pine tortrix	Larvae mine needle sheaths when new shoots development is nearly complete.
Lepidoptera:Pieridae	<i>Neophasia menapia</i>	pine butterfly	Larvae generally attack older trees throughout the summer consuming new and old foliage.
Lepidoptera:Saturniidae May of the	<i>Coloradia pandora</i>	pandora moth	Larvae present beginning in August. Defoliation noticeable in following year.
Lepidoptera:Arctiidae	<i>Halisidota ingens</i>	webworm	Larvae construct webs on young trees and feed on upper foliage.
Lepidoptera:Lymantriidae	<i>Orgyia pseudotsugata</i>	douglas-fir tussock moth	Larvae feed on unfolding new needles causing them to die which gives the tree a strong reddish cast. As larvae mature, they feed on both new and old foliage through the summer.

Table 1.--Ponderosa pine foliage feeding insects and the nature of their feeding damage. (Continued)

Order/Family	Scientific Name	Common Name ¹	Nature of Feeding
Lepidoptera:Lymantriidae	<i>Parorgyia grisefacta</i>	pine tussock moth	Larvae feed on young pine during late summer and the following spring.
Lepidoptera:Noctuidae	<i>Euxoa excellens</i>	cutworm	Larvae feed on young seedlings in spring, damaging cotyledons and stems. Can be economical pests of nurseries.
Lepidoptera:Yponomeutidae	<i>Zelleria haimbachi</i>	pine needle sheathminer	Larvae feed on new growth throughout summer and the following spring. Feed at bases of needle clusters causing them to drop, die, and shed prematurely.
Lepidoptera:Gelechiidae	<i>Coleotechnites</i> spp.	needle miners	Sustained and destructive outbreaks can result in heavy discoloration and kill trees extensively.
Homoptera:Aphididae	<i>Pineus Coloradensis</i>	pine adelgid	The foliage of heavily attacked trees becomes yellowish and growth is retarded; white, waxy secretions are conspicuous on seedlings.
Homoptera:Diaspididae	<i>Nuculaspis californica</i>	black pine leaf scale	Sustained, heavy infestations for several years can weaken and kill trees of all sizes. Significantly affected trees have sparse, short foliage at the tips of branches.
Homoptera:Margaroididae	<i>Matsucoccus</i> spp.	pine scale	Epidemic populations in Arizona and New Mexico have caused extensive twig blight.
Hymenoptera:Diprionidae	<i>Neodiprion</i> spp.	pine sawflies	Larvae generally feed on pole-sized trees, but attack trees of all ages depending on the species. Feeding can weaken affected trees and reduce growth; mortality may also occur. Under some conditions sawflies can cause defoliation over an extensive area.

¹Common names based on Sutherland (1978) or Furniss and Carolin (1977).

Methods to quantitatively assess potential impacts

Because of paucity of data, qualitative judgments were used to initially assess the foliage feeding insects. The insects selected were assigned relative values according to their feeding habits and life histories. Based on our knowledge of defoliation patterns of individual species and the hypothetical response functions

developed from the literature, we categorized defoliators into impact intensity groups.

The insects were assessed for factors which influence timber production and scenic beauty (Table 2). For timber production these factors included: (1) preponderance for species outbreak, (2) age class of foliage fed upon, and (3) season of feeding. And factors evaluated which affect scenic beauty included: (1) prepon-

Table 2.--Criteria used to qualitatively assess the affects of foliage feeding insects on timber production and scenic beauty.

I. Timber

- A. Preponderance for Outbreak
 0 - no evidence of outbreak
 1 - rarely reaches epidemic levels
 2 - evidence of outbreak, but infrequent and not destructive
 3 - frequent outbreaks, but not destructive or sustained
 4 - infrequent outbreaks, destructive and sustained
 5 - frequent, sustained periods of destructive outbreak
- B. Age Class of Foliage Being Fed Upon
 0 - partial old growth
 1 - complete old growth
 2 - partial new growth
 3 - partial new growth and old growth
 4 - complete new growth
 5 - complete new growth and old growth
- C. Seasonal Timing of Feeding
 0 - partial, pre-needle expansion
 1 - complete, pre-needle expansion
 2 - partial, early summer, post-needle expansion
 3 - partial, late summer, post-needle expansion
 4 - complete, early summer, post-needle expansion
 5 - complete, late summer, post-needle expansion

II. Scenic Beauty

- A. Preponderance for Outbreak
 0 - no evidence of outbreak
 1 - rarely reaches epidemic levels
 2 - evidence of outbreak, but infrequent and not destructive
 3 - frequent outbreaks, but not destructive or sustained
 4 - infrequent outbreaks, destructive and sustained
 5 - frequent, sustained periods of destructive outbreak
- B. Distribution of Feeding Damage
 0 - sparsely scattered over small area
 1 - sparsely scattered over large area
 2 - moderate over small area
 3 - moderate over large area
 4 - heavy over small area
 5 - heavy over large area
- C. Discoloration Due to Feeding Damage
 0 - no discoloration
 1 - light discoloration, or unsightly feeding habits
 2 - moderate discoloration, short period
 3 - moderate discoloration, extended period
 4 - heavy discoloration, short period
 5 - heavy discoloration, extended period

Table 3.--Selected foliage feeding insects of ponderosa pine qualitatively assessed for timber production and scenic beauty.¹

Species	Timber	Scenic Beauty	Species	Timber	Scenic Beauty
<i>Glyptoscelis illustris</i>	A. 1 B. 2 C. <u>2</u> 5	A. 1 B. 3 C. <u>0</u> 4	<i>Scythropus californicus</i>	A. 2 B. 0 C. <u>2</u> 4	A. 2 B. 0 C. <u>2</u> 4
<i>Phyllophaga falsa</i>	A. 2 B. 2 C. <u>2</u> 6	A. 2 B. 4 C. <u>2</u> 8	<i>Choristoneura lambertiana</i>	A. 4 B. 4 C. <u>3</u> 11	A. 4 B. 3 C. <u>4</u> 11
<i>Cylindrocopturus eatoni</i>	A. 2 B. 2 C. <u>2</u> 6	A. 2 B. 3 C. <u>3</u> 8	<i>Neophasia menapia</i>	A. 4 B. 5 C. <u>4</u> 13	A. 4 B. 5 C. <u>1</u> 10

Table 3.--Selected foliage feeding insects of ponderosa pine qualitatively assessed for timber production and scenic beauty¹ (Continued)

Species	Timber	Scenic Beauty
<i>Coloradia pandora</i>	A. 4 B. 1 C. $\frac{1}{6}$	A. 4 B. 5 C. $\frac{0}{9}$
<i>Halisidota ingens</i>	A. 1 B. 2 C. $\frac{2}{5}$	A. 1 B. 3 C. $\frac{2}{6}$
<i>Orgyia pseudotsugata</i>	A. 4 B. 5 C. $\frac{4}{13}$	A. 4 B. 5 C. $\frac{4}{13}$
<i>Parorgyia grisefacta</i>	A. 2 B. 3 C. $\frac{3}{8}$	A. 2 B. 3 C. $\frac{3}{8}$
<i>Euxoa excellens</i>	A. 1 B. 2 C. $\frac{2}{5}$	A. 1 B. 0 C. $\frac{0}{1}$
<i>Zelleria haimbachi</i>	A. 3 B. 2 C. $\frac{1}{6}$	A. 3 B. 2 C. $\frac{5}{10}$

Species	Timber	Scenic Beauty
<i>Coleotechnites</i> spp.	A. 5 B. 1 C. $\frac{2}{8}$	A. 5 B. 5 C. $\frac{5}{15}$
<i>Neodiprion</i> spp.	A. 3 B. 3 C. $\frac{2}{8}$	A. 3 B. 2 C. $\frac{0}{5}$
<i>Pineus coloradensis</i>	A. 2 B. 2 C. $\frac{2}{6}$	A. 2 B. 2 C. $\frac{3}{7}$
<i>Nuculaspis californica</i>	A. 3 B. 4 C. $\frac{3}{10}$	A. 3 B. 3 C. $\frac{3}{9}$
<i>Matsucoccus</i> spp.	A. 2 B. 3 C. $\frac{3}{8}$	A. 2 B. 4 C. $\frac{5}{11}$

¹The assessment values assigned to species pertain to the criteria listed in Table 2.

derance for species outbreak, (2) distribution of feeding damage, and (3) discoloration patterns due to feeding damage. The assigned values were then totaled and used to place the defoliators into impact intensity categories.

Results of quantitative assessment

To determine in which of the three impact intensity categories (high, moderate, or low) a species was placed, the qualitative assessment values derived in Table 3 were summed for timber and scenic beauty (Table 4). While the majority of species were placed in the same intensity category for both timber production and scenic beauty, there were some notable exceptions.

Orgyia pseudotsugata and *Choristoneura lambertiana* (Busck) have been frequently documented as being important economical pests of timber production (Furniss and Carolin 1977). Because of their recurrent population outbreaks which cause widespread defoliation of new needles and, in the case of *O. pseudotsugata*, strong discoloring of needles, these species can be considered to impact scenic beauty. While

Neophasia menapia appears in the high impact intensity category for timber production, its impact on scenic beauty is relatively lower due to the nature of its feeding (complete defoliation compared with discoloration). For *Coleotechnites* spp. and *Matsucoccus* spp. the reverse is true. That is, these species have a high impact on scenic beauty, but only moderate impacts on timber production, owing to their feeding damage which causes extensive discoloration.

Insects placed in the moderate impact intensity category, although usually not regarded as economical pests of timber products, may cause significant damage to timber products and scenic beauty. The level of damage depends on whether populations reach epidemic proportions and on the timing of feeding or the nature of feeding damage. *Zelleria haimbachi* (Busck) has moderate impacts on timber production because of its normally low defoliation intensity early in the summer, but the resulting discoloration of needles it causes may lead to a strong negative impact on scenic beauty. Similarly, *Coloradia pandora* may have potentially

Table 4.--Ranking of selected species according to their relative impact on timber production and scenic beauty. The numbers in parentheses pertain to the total qualitative impact rating determined in table 4.

Impact Intensity	Timber Production		Scenic Beauty	
High (11-15)	<i>Orgyia</i>	(13)	<i>Coleotechnites</i>	(15)
	<i>pseudotsugata</i>		spp.	
	<i>Neophasia</i>	(13)	<i>Orgyia</i>	(13)
	<i>menapia</i>		<i>pseudotsugata</i>	
	<i>Choristoneura</i>	(11)	<i>Choristoneura</i>	(11)
	<i>lambertiana</i>		<i>lambertiana</i>	
			<i>Matsucoccus</i>	(11)
			spp.	
Moderate (6-10)	<i>Nuculaspis</i>	(10)	<i>Neophasia</i>	(10)
	<i>californica</i>		<i>menapia</i>	
	<i>Parorgyia</i>	(8)	<i>Zelleria</i>	(10)
	<i>grisefacta</i>		<i>haimbachi</i>	
	<i>Coleotechnites</i>	(8)	<i>Coloradia</i>	(9)
	spp.		<i>pandora</i>	
	<i>Neodiprion</i>	(8)	<i>Nuculaspis</i>	(9)
	spp.		<i>californica</i>	
	<i>Matsucoccus</i>	(8)	<i>Phyllophaga</i>	(8)
	spp.		<i>falsa</i>	
	<i>Phyllophaga</i>	(6)	<i>Cylindrocopturus</i>	(8)
	<i>falsa</i>		<i>eatoni</i>	
	<i>Cylindrocopturus</i>	(6)	<i>Parorgyia</i>	(8)
	<i>eatoni</i>		<i>grisefacta</i>	
	<i>Coloradia</i>	(6)	<i>Pineus</i>	(7)
	<i>pandora</i>		<i>coloradensis</i>	
	<i>Zelleria</i>	(6)	<i>Halisidota</i>	(6)
	<i>haimbachi</i>		<i>ingens</i>	
	<i>Pineus</i>	(6)		
	<i>coloradensis</i>			
Low (0-5)	<i>Glyptoscelis</i>	(5)	<i>Neodiprion</i>	(5)
	<i>illustris</i>		spp.	
	<i>Halisidota</i>	(5)	<i>Glyptoscelis</i>	(4)
	<i>ingens</i>		<i>illustris</i>	
	<i>Euxoa</i>	(5)	<i>Scythropus</i>	(4)
	<i>excellens</i>		<i>californicus</i>	
	<i>Scythropus</i>	(4)	<i>Euxoa</i>	(1)
	<i>californicus</i>		<i>excellens</i>	

high negative affects on scenic beauty because of its heavy feeding damage over a large area (albeit with no discoloration), but a relatively low impact on timber production due to its feeding on primarily previous year needles. In contrast, *Neodiprion* spp. may have a moderately high impact on timber production under certain conditions, while not inducing major impacts on scenic beauty because their feeding damage results in little discoloration usually over a small area.

Foliage feeding insects that ranked in the low impact intensity category may have relatively minor affects on timber production and scenic beauty due to the rarity of species out-

break, age class of foliage being damaged, seasonal timing of feeding, and/or the nature of the species feeding damage. For example, *Euxoa excellens* (Grote') rarely reaches epidemic levels and partially defoliates early in the summer over small areas. Therefore, although it can be an important pest of tree nurseries (Furniss and Carolin 1977), the impacts on natural forests are minimal. Likewise *Scythropus californicus* (Horn), which feeds on old foliage of ponderosa pine in spring and early summer, causes feeding damage that is sparsely scattered over small areas.

Implications

We have proposed in this paper a procedure to estimate the impact of some insects based on the patterns of defoliation without formal experiments. The procedure begins with reviewing literature to discover general patterns of impacts on timber or non-timber products effected by foliage feeding insects. These patterns are then used to develop hypothetical relationships as a function of the agent causing the impact and the multiresource output. Based on the relationships, criteria are derived by which the specific agent is qualitatively assessed. The resulting estimations serve as a guide to assessing impacts. It is important to point out that the methodology of this procedure is limited to species specific effects, and is not appropriate for evaluating factors which are independent of species.

Experimental verification of these response functions is critical prior to their widespread application. The procedure outlined above serves as a method to qualitatively assess potentially important insects and insect affects on timber and scenic beauty for further study. It is clear from analysis that some insect species warrant considerably more research attention than they have received to date. For example, the qualitative evaluations in this paper lead us to recognize that some non-economical species from a timber perspective could be very important from a scenic beauty standpoint (e.g. *Coleotechnites* species). More research on life histories of individual defoliating species needs to be performed to better understand the full impact of the defoliator. The methods developed here may have utility for other non-timber products such as recreation or wildlife. Ideally, a defoliating species would be assessed for its impacts on all multiresource outputs; and the impacts simultaneously weighed. This would enable the forest manager to make the most highly qualified decision on whether to implement pest control practices or to consider the species as an economical pest.

LITERATURE CITED

- Anderson, L.M. 1981. Land use designations affect perception of scenic beauty in forest landscapes. *Forest Science* 27:392-400.
- Barbosa, P., and M.R. Wagner. 1989. *Introduction to Forest and Shade Tree Insects*. Academic Press. San Diego CA. 639 pp.
- Britton, R.J. 1988. Physiological effects of natural and artificial defoliation on the growth of young crops of lodgepole pine. *Forestry* 61:165-175.
- Buhyoff, G.J., and W.A. Leuschner. 1978. Estimating physiological disutility from damaged forest stands. *Forest Science* 24:424-432.
- Buhyoff, G.J., J.D. Wellman, and T.C. Daniel. 1982. Predicting scenic quality for mountain pine beetle and western spruce budworm damaged forest vistas. *Forest Science* 28:827-838.
- Cole, W.E. 1966. Effect of pine butterfly defoliation on ponderosa pine in Southern Idaho. USDA Forest Service Research Note INT-146. Intermountain Forest and Range Experiment Station. Ogden, Utah.
- Furniss, R.L., and V.M. Carolin. 1977. *Western Forest Insects*. USDA Forest Service Miscellaneous Publication 1339. 654 pp.
- Kozlowski, T.T. 1971. *Growth and Development of Trees*, Vol. 1. Academic Press, New York, N.Y. 514 pp.
- Krisko, K.A. 1988. Insect defoliation, interpretation, and recreation value at Grand Canyon National Park, Arizona. Master of Science thesis. Northern Arizona University. 5-50 pp.
- Kulman, H.M. 1965. Effects of artificial defoliation of pine on subsequent shoot and needle growth. *Forest Science* 11:90-98.
- Kulman, H.M. 1971. Effects of insect defoliation on growth and mortality of trees. *Annual Review of Entomology* 16:289-324.
- Leuschner, W.A., and R.L. Young. 1978. Estimating southern pine beetle's impact on reservoir campsites. *Forest Science* 24(4):527-537.
- Mattson, W.J., and N.D. Addy. 1975. Phytophagous insects as regulators of forest primary production. *Science* 190:515-522.
- Ribe, R.G. 1989. The aesthetics of forestry: what has empirical preference research taught us? *Environmental Management* 13(1):55-74.
- Stevens, R.E. 1973. A ponderosa pine needle miner in the Colorado front range. USDA Forest Service Research Note RM-228. 4 pp. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.
- Stevens, R.E., and D.A. Leatherman. 1982. Implants and sprays for control of ponderosa pine needle miner in foliage of individual trees. USDA Forest Service Research Note RM-420. 4 pp. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.
- Sutherland, D.W.S. 1978. *Common Names of Insects and Related Organisms (1978 Revision)*. Entomological Society of America. College Park, Maryland. 132 pp.

Incorporating Pest Management into Land Management Decisions¹

Borys M. Tkacz²

Abstract.--Implementation of Forest Plans in the Southwestern Region of the USDA Forest Service is following the Integrated Resource Management (IRM) philosophy which recognizes the intricate inter-relationships between all the natural resources. Forest Pest Management specialists are involved in all phases of IRM, from the initial development of project concepts and identification of concerns and opportunities related to insects and diseases to the analysis of treatment alternatives and the eventual project implementation and monitoring of success.

INTRODUCTION

A large portion of the public perceives a decline in the health of our Nation's forests. These concerns were partially triggered by recent outbreaks of gypsy moth, southern pine beetle, western spruce budworm and mountain pine beetle, as well as, publicity about the effects of atmospheric pollution on forests. In response to concerns emphasized by Members of Congress, the USDA Forest Service recently completed a report titled: "Forest Health Through Silviculture and Integrated Pest Management: A Strategic Plan" (U.S. Department of Agriculture 1988a). The objective of this plan is to "enhance and maintain the health of the Nation's forests ... through Forest Service programs and authorities". Forest health is defined as "a condition where biotic and abiotic influences on the forest (i.e. insects, diseases, atmospheric deposition, silvicultural treatments, harvesting practices) do not threaten management objectives for a given forest unit now or in the future".

One of the issues identified in this report was that pest management considerations are not adequately incorporated in forest resource management planning processes. Most Forest Plans mention but do not provide for practicing pest

management and priorities for forest management activities rarely consider forest pest impacts. Most Forest Plan analyses projecting productivity did not make necessary adjustments for potential losses to forest pests. Failure to consider forest pest impacts in Forest Plan implementation projects could exacerbate existing and potential pest problems. The report recommends that the USDA Forest Service "require pest specialist input to National Forest System inter-disciplinary teams conducting forest resource management planning" (U.S. Department of Agriculture 1988a).

This presentation will outline how land managers and Forest Pest Management (FPM) specialists in the Southwestern Region are working toward incorporating pest management into land management decisions on a project-by-project basis.

PESTS OF PONDEROSA PINE

Management of ponderosa pine (*Pinus ponderosa* Laws. subsp. *scopulorum* Murray) in the Southwest is complicated by several pests. The most important disease is caused by southwestern dwarf mistletoe (*Arceuthobium vaginatum* (Wild.) Presl subsp. *cryptopodum* (Engelm.) Hawksw. & Wiens) (Beatty 1982). Recent surveys indicate that 39 percent of the commercial ponderosa pine acres on National Forests in Arizona and New Mexico are infected resulting in an annual loss in productivity of at least 20 million cubic feet per year (MMCF), or approximately 14 percent of estimated potential productivity (H. Maffei, personal communication, 1989). Root diseases caused by *Armillaria* sp. and

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²Borys M. Tkacz is Arizona Zone Leader for Forest Pest Management, Southwestern Region, USDA Forest Service, Flagstaff, AZ.

Heterobasidion annosum (Fr.) Bref. annually kill an estimated 1.0 MMCF of ponderosa pine in Arizona and New Mexico (Wood 1983). Bark beetles, including engraver beetles (Ips spp.), western pine beetle (Dendroctonus brevicomis LeConte), and mountain pine beetle (Dendroctonus ponderosae Hopkins), are periodically destructive to ponderosa pines in the Southwest. Estimated volume losses caused by these insects in 1988 approximated 0.9 MMCF in Arizona and New Mexico (Rogers and Maffei 1989).

INTEGRATED RESOURCE MANAGEMENT

Forest health is a desired future condition. Although most Forest Plans gave us specific management objectives by area, they did not present a very clear picture of the desired forest conditions to meet them. Clear descriptions of desired future conditions for specific sites are needed for implementation of Forest Plans.

Implementation of Forest Plans in the Southwestern Region is following the Integrated Resource Management (IRM) philosophy which recognizes the intricate interrelationships between all the natural resources (U.S. Department of Agriculture 1988b). An inter-disciplinary (ID) approach is being utilized to design impact generating projects. Attempts are made to identify the resources involved, define the resource interrelationships and to reasonably predict the effects or impacts of projects. Project design and implementation follows a 13-phase process that closely parallels the NEPA (National Environmental Policy Act of 1969) process (fig. 1.). Forest Pest Management specialists in the Southwestern Region are involved throughout all phases of IRM.

To illustrate how pest management is incorporated into land management I will present the development of a timber sale on the Payson Ranger District of the Tonto National Forest. The Meads Timber Sale is located about 12 miles northeast of Payson, Arizona. The assessment area encompasses 5862 acres excluding 263 acres of private land. Timber stands within the analysis area consist of ponderosa pine and are generally 2 to 3 storied in structure. The most prevalent management age class is immature sawtimber (12-13 inches in diameter at breast height (DBH)) with small poles (6-9 inches DBH), large poles (9-12 inches DBH) and seedlings and saplings being about equally represented, but not equally distributed. There is a significant amount of woodland type (juniper/oak) within the analysis area. Past practices have included precommercial thinning pole stands and pulpwood and salvage harvesting with no attempts to provide for even-aged stands or to control dwarf mistletoe. Dwarf mistletoe infection of ponderosa pine is widespread within the analysis area.

SCOPING

- 1 REVIEW FOREST PLAN
- 2 DEVELOP PROJECT CONCEPT
- 3 CONDUCT EXTENSIVE RECON.
- 4 FEASIBILITY REPORT

ANALYSIS

- 5 IMPLEMENTATION SCHEDULE
- 6 INTENSIVE RECON.
- 7 GENERATE ALTERNATIVES
- 8 SELECT ALTERNATIVE

DOCUMENTATION

- 9 ENVIRONMENTAL DOCUMENT

IMPLEMENTATION

- 10 PROCESS RECORDS
- 11 PROJECT ACTION PLAN
- 12 IMPLEMENTATION

MONITORING

- 13 MONITORING & EVALUATION

Figure 1.--Project implementation through Integrated Resource Management as it relates to the NEPA process.

SCOPING

The first phase in project planning is to determine how the proposed project may contribute to the accomplishment of Forest Plan goals and objectives and whether it conforms with standards and guidelines. Forest goals are desired conditions to be achieved sometime in the future. The Tonto National Forest Plan contains the following goal: "Through integrated pest management, manage resources to prevent a build-up of insects and diseases to prevent or reduce serious, long lasting hazards" (U.S. Department of Agriculture 1985). Forest objectives are measurable, planned outputs of resources that respond to pre-established goals. The timber yield projections on the Tonto National Forest included the effects of dwarf mistletoe as predicted by the RMYLD growth and yield simulator (Edminster 1978).

Forest-wide standards and guidelines provide general indications of policy. For example: "Important Forest insects and diseases will be monitored on an annual basis. Where conditions

indicate an impending build-up or outbreak is imminent, an evaluation will be conducted in order to formulate management alternatives to reduce loss to an acceptable level" (U.S. Department of Agriculture 1985).

More specific standards and guidelines are listed for each Management Area. These are mapped areas that have a common direction throughout that differs from neighboring areas. The Meads Timber Sale is within the 4D Management Area as identified by the Tonto National Forest Plan. Management emphasis is to manage for a variety of renewable resource outputs with primary emphasis on intensive, sustained yield timber management, timber resource protection, creation of wildlife habitat diversity, increased populations of emphasis harvest species, and recreation opportunity. Standards and guidelines for Management Area 4D include the following: "Integrate dwarf mistletoe surveys into stand examinations. Remove infected overstories as soon as regeneration is accomplished. Thin understories to densities which will maximize fiber production, and therefore stand vigor, using yield simulation models as guides. Eradicate infected stands by clear-cutting and regenerate artificially when simulation models indicate that they will not reach maturity because of mistletoe." (U.S. Department of Agriculture 1985).

Any conflicts in the standards and guidelines need to be identified and addressed during this initial stage of project planning. For example, conflicting guidelines may exist for visual management and dwarf mistletoe management.

The next phase in the IRM process is to develop the project concept. The objective is to determine precisely what this project will be designed to do and why. This is done by identifying the site specific issues, concerns, and opportunities through initial scoping meetings of the ID Team, specialists and consultants, and interested publics. Project objectives are then developed to accomplish the opportunities, mitigate the concerns and resolve the issues.

Site specific public issues for the Meads Timber Sale were identified during public meetings. These included concerns about mistletoe infestation surrounding private land, and types of slash treatments. Forest Pest Management specialists participated in developing the project concept by providing pest related management concerns and opportunities. One of the management concerns for the Meads Timber Sale was managing timber resources with the adverse combination of a narrow age class distribution, multi-storied stand structure, and severe dwarf mistletoe infestation. Opportunities included treating dwarf mistletoe through harvesting and post-sale treatments, improving age class diversity, and educating the public on IRM, silvicultural practices, and mistletoe control.

The objectives developed for the Meads Timber Sale included managing the timber resource through silvicultural treatments to promote growth and reduce mortality, generating sawtimber, pulpwood, and fuelwood for public and commercial utilization, managing for improvement of wildlife habitat and watershed conditions, and reducing fire hazard by treating fuels. The activities proposed were timber harvest, residue disposal, reforestation, thinning, forage production, and wildlife habitat and watershed improvement.

ANALYSIS

One of the most critical phases of project preparation is intensive reconnaissance. Members of the ID Team and other specialists assemble or collect all of the site specific information needed to design a project that suits its unique location and objectives. Attempts are made to interrelate the various resources which exist within the area. The entire ID Team and consulting specialists may visit the project site to verify and refine the issues, concerns, and opportunities identified in the earlier phases and to identify project design specifics.

Analysis of silvicultural treatment needs actually begins earlier in the project planning process. Silvicultural treatment diagnoses are prepared following detailed stand examinations. Results of these exams are detailed descriptions of stand structure and composition and pest incidence and severity. Stand exams for the Meads Timber Sale were supplemented by FPM funds in 1985 to collect more intensive data on dwarf mistletoe infested stands. The silviculturist then prepared a diagnosis of treatment needs for each stand in the assessment area. The diagnoses defined individual stand objectives, described present stand conditions, and proposed treatments to develop conditions that would best satisfy the objectives. Stand priorities for treatment were developed to rank stands within the assessment area. High priority stands were multi-storied with dwarf mistletoe infection in the overstory that could infect an adequately stocked understory. Medium priority stands were mistletoe-infected, even-aged stands where the disease could be controlled through silvicultural treatment. Low priority stands were those where dwarf mistletoe was not a problem and regeneration was not diagnosed.

A separate, more intensive survey was conducted in 1988 surrounding the private lands within the Meads Timber Sale Area. The objective was to identify areas where silvicultural treatment could prevent spread of dwarf mistletoe onto or from private lands. Pest specialists from Arizona State Forestry Division worked with landowners in the residential developments to encourage treatment of dwarf mistletoe on private lands.

Forest Pest Management was involved in the reconnaissance phase of analysis for the Meads Timber Sale by visiting specific stands within the assessment area with the silviculturist to discuss diagnosed treatments to deal with the dwarf mistletoe problem. A biological evaluation was prepared to ensure that the proposed treatments were biologically sound and that they met the dwarf mistletoe management objectives identified earlier. Alternative ways of treating uneconomic stands were discussed, such as funding sanitation thinning with FPM pest suppression funds or sale area improvement funds.

The next phase in project planning is alternative generation and comparison. The objective is to develop and compare a reasonable range of alternatives including a "No Action" alternative. Specific alternatives to deal with pest situations may be developed by the ID Team. Since the priorities for silvicultural treatment for the Meads Timber Sale did not change by alternative, all the action alternatives considered dwarf mistletoe management to some degree. Alternative 1 treated selected stands that met the following criteria: 1) high or medium silvicultural treatment priority, 2) dwarf mistletoe infection of ponderosa pine, and 3) economic to harvest based on projected road construction costs. Alternative 2 treated selected stands that were: 1) high or medium silvicultural treatment priority, and 2) dwarf mistletoe infected regardless of economic feasibility. Alternative 3 treated all stands identified in Alternative 1 along with a priority list of potential stands that would become feasible as small salvage sales with supplemental funding. Alternative 4 was the "No Action" alternative.

The next phase of IRM is to compare and evaluate alternatives with respect to environmental effects, accomplishment of project objectives, and economic feasibility. Evaluation criteria for comparison of alternatives may include some measure of pest suppression or prevention, such as, acres treated for mistletoe or acres with reduced bark beetle hazard. Alternative 4 (no action) for the Meads Timber Sale would have prevented opportunities for wildlife habitat and range improvements, fuel management, and visual enhancements. The effects of no action would be further deterioration of forest health due to intensification and spread of dwarf mistletoe. Alternative 2 would treat the most acreage of timber with mistletoe infection and produce the most volume but it had the highest road cost per timber volume removed. Alternative 3 would treat the same acreage if all additional potential stands were funded. The supplemental treatment of mistletoe in Alternative 3 would provide the best benefit for visual quality by prevention of mistletoe spread and subsequent mortality. The ID Team recommended that Alternative 3 be the preferred alternative. This alternative would achieve an economical sale, provide for the most acreage of mistletoe treatment, improve age class

diversity, and provide an opportunity to treat mistletoe infestation and manage fuels around private lands.

DOCUMENTATION

The responsible official selects the preferred action from a range of alternatives and determines appropriate NEPA documentation to fully comply with regulations. Pest management documents or information may need to be included or referenced in the NEPA documentation. An Environmental Assessment was prepared for the Meads Timber Sale. The Forest Supervisor determined that this was not a major action that would significantly affect the quality of the human environment and, therefore, an environmental impact statement was not needed. In the Decision Notice the Forest Supervisor stated that the preferred alternative was Alternative 3 because it provided for an economically viable sale that treated the most acreage of dwarf mistletoe, improved conditions for future timber production, and improved the age class diversity which benefits wildlife.

IMPLEMENTATION

During the preparation of project action plans, FPM specialists provide assistance in project layout and development of contract provisions. For example, special contract provisions may be required for low elevation ponderosa pine stands to prevent infestation by Ips bark beetles. These provisions may call for utilization of trees to a 4 inch top, limiting cutting to specific seasons (July to December), or requiring prompt removal or treatment of suitable brood material (Parker 1979). Forest Pest Management specialists may also be involved in field review of final silvicultural prescriptions, cutting unit layout, and timber marking guidelines.

Unexpected circumstances during project implementation may require modification of the action plan with input from FPM specialists. For example, abnormally dry conditions may increase risk of bark beetle infestation.

MONITORING

Once the project is completed FPM specialists assist in monitoring project effectiveness. Post treatment evaluations are conducted to determine if project objectives were met. Evaluation results are used to modify or improve pest management strategies for future projects.

CONCLUSIONS

The Meads Timber Sale provides an example of how pest management can be incorporated into the development of a timber sale. The IRM process is also utilized to provide pest management input into other types of projects. Forest Pest Management specialists have participated in the development of new recreation sites where forest pests are a concern. Surveying of proposed sites prior to design and development is the best way to avoid future problems. For example, surveys of a proposed campground may reveal pockets of root disease that should be avoided to reduce tree mortality and hazard to recreationists. Forest Pest Management specialists have also provided input to ID teams analyzing ski area expansion, salvage sales following burns, and wilderness area management.

In the Southwestern Region, we are working toward incorporating pest management considerations into project plans through the IRM process. By being involved in all phases of IRM, from the initial development of project concepts to the eventual implementation and monitoring of success, Forest Pest Management is insuring that pest effects are considered in land management decisions. Hopefully, this will help us leave a healthier forest than we inherited.

LITERATURE CITED

Beatty, Jerome S. 1986. Integrated Forest Protection Guide. Southwestern Dwarf Mistletoe, Arceuthobium vaginatum subsp. cryptopodum (Engelm.) Hawks. & Weins, in Ponderosa Pine. USDA Forest Service Forest Pest Management Report R3-82-13, 12 p. Southwestern Region, Albuquerque, NM.

Edminster, Carelton B. 1978. RMYLD: Computation of yield tables for even-aged and two-storied stands. USDA Forest Service Research Paper RM-199. 26 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

Parker, Douglas L. 1979. Integrated Pest Management Guide. Arizona Five-spined Ips, Ips lecontei Swaine, in Ponderosa Pine. USDA Forest Service Forest Pest Management Report R3-79-12. 17 p. Southwestern Region, Albuquerque, NM.

Rogers, Terrence J. and Helen M. Maffei. 1989. Annual Southwestern Region Pest Conditions Report. USDA Forest Service Forest Pest Management Report R3-89-2. 17 p. Southwestern Region, Albuquerque, NM.

U.S. Department of Agriculture, Forest Service. 1985. Tonto National Forest Plan. 257 p. USDA Forest Service, Southwestern Region, Tonto National Forest, Phoenix, AZ. [unnumbered publication]

U.S. Department of Agriculture, Forest Service. 1988a. Forest Health Through Silviculture and Integrated Pest Management - A Strategic Plan. edited by Tim McIntire. 26 p. USDA Forest Service. Washington, D.C. [unnumbered publication]

U.S. Department of Agriculture, Forest Service. 1988b. Project Implementation Process for Integrated Resource Management (2nd Edition). 36 p. USDA Forest Service, Southwestern Region, Albuquerque, NM. [unnumbered publication]

Wood, Robert E. 1983. Mortality caused by root diseases and associated pests on six National Forests in Arizona and New Mexico. USDA Forest Service Forest Pest Management Report R3-83-13. 31 p. Southwestern Region, Albuquerque, NM.

Effects of Controlled Grazing of Understory Grasses and Forbs on Survival and Growth of Ponderosa Pine Seedlings¹

David A. Koehler, Stephen D. Thomas, Harold D. Russell, and Jerome A. Mastel²

Abstract--A case history of Piney Burn on the Navajo Reservation in northeast Arizona is described. The man-caused fire which occurred in 1977 encompassed 145 ha. In the following year, a regeneration project was established with containerized Ponderosa pine seedlings. Concern over accelerated erosion prompted a decision to also aerially seed adapted grasses and forbs. The subsequent failure of the plantation was attributed to competition from the grass-forb understory. Another reforestation project was initiated in 1981. After three growing seasons, surveys indicated that competition from the understory was seriously inhibiting conifer growth. Experimental trials in 1985 were implemented that utilized randomized block designs on twelve (12) plots to evaluate the effects of manual scalping, herbicide (low rate), herbicide (high rate) and control treatments on survival and growth of pine seedlings. Mechanical defoliation significantly enhanced ($P < 0.05$) both height and diameter of seedlings in the first growing season. Chemical defoliation increased only height ($P < 0.05$). Concurrently, heavy grazing by cattle in two 0.8 ha enclosures effectively reduced vegetative competition and caused only about one percent conifer mortality.

During 1986-89, the entire area was divided into three units to investigate grazing effects on conifer canopy, density, height and diameter. The treatments were: no grazing, moderate grazing in alternate years and moderate grazing in consecutive years. These treatments were not replicated. However, the data suggest that highest grazing frequency was associated with greater values for canopy cover and the growth parameters, height and basal diameter. Density of conifer seedlings was apparently not enhanced or reduced by grazing treatments.

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²David A. Koehler, Area Supervisory Range Conservationist, Bureau of Indian Affairs, Navajo Area Office, P. O. Box M, Window Rock, AZ 86515.

Stephen D. Thomas, Forester, Bureau of Indian Affairs, Jicarilla Agency, P. O. Box 167, Dulce, NM 87528.

Harold D. Russell, Forester, Bureau of Indian Affairs, Navajo Area Office, P. O. Box M, Window Rock, AZ 86515.

Jerome A. Mastel, Range Conservationist, Bureau of Indian Affairs, Navajo Area Office, P. O. Box 1060, Gallup, NM 87305.

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INTRODUCTION

In their respective professional sectors, livestock production and timber regeneration were perceived as mutually exclusive for many years. These perceptions were based on histories of overgrazing by domestic livestock on many Southwestern forests. Uncontrolled grazing has frequently resulted in trampling, browsing and the ultimate mortality of young conifers. As intensity and duration of livestock use increases, the likelihood of conifer browsing becomes greater because more palatable forages are eliminated. These conflicts are especially extreme on Ponderosa pine forests of the Navajo Reservation where competition for resources becomes more intensified with each generation. In the latter locale, grazing by several classes of livestock has continued without restrictions for more than one hundred years, often to the extreme detriment of Ponderosa pine regeneration.

In other areas of Ponderosa pine-bunchgrass ranges, voluntary restrictions are enforced by recognition of the toxicological effects of pine needles in cattle. The primary effects are abortion and associated complications (Panter and James 1987). Risks of these effects can be minimized by intensive management. The incidence of abortion is most high when pine needles are ingested close to the time of normal parturition. Most of the abortions in cows eating pine foliage generally occur in the late fall, winter or early spring, the period that corresponds to the third trimester of pregnancy. The factors that are believed to cause pregnant cows to browse pine needles include stress, lack of familiar or high quality feed, sudden access to pine needles (e.g., windfalls), boredom or curiosity and accidental ingestion with other feed. Most managers and stockgrowers, however, believe that Ponderosa pine-bunchgrass ranges can be safely grazed if timing and intensity of use are closely monitored.



Figure 1.--Grass-forb understory on Piney Burn resulting from aerial seeding inhibited establishment and growth of conifer seedlings

Recently, the use of domestic livestock as biological agents for control of unwanted vegetation has increased because of the obvious economic and environmental benefits of these procedures (Hedrick 1975; Wood 1987). A biological agent is described by Brock (1988) as an "organism that has an action leading to the destruction of another organism (host) or weakens it so that pathogens attack it or make it competitive with other organisms...". Sheep and goats are the most common domestic biological agents. Cattle generally have a lesser potential for biological control because forbs and shrubs that are commonly regarded to be pest species are not preferred constituents of their diets. One considerable advantage of prescribed livestock grazing over chemical or mechanical controls is that unwanted, competitive vegetation may be removed while marketable animal products are simultaneously produced (Sharrow et al. 1989). This advantage is contingent upon two conditions being met: (1) livestock must utilize the unwanted vegetation while not significantly damaging the commercially valuable species, and (2) target species must not regrow substantially after grazing/browsing.

The most recent technical literature reports growing evidence that prescribed or controlled livestock grazing can be successfully used to promote establishment and growth of conifer seedlings when numbers, distribution and timing of use can be strictly controlled. Doescher et al. (1987) caution that the following factors must be observed when livestock are used to suppress competing vegetation: (1) palatable forage must be available to minimize conifer damage, (2) when moisture is limiting, vegetation should be grazed before stored soil moisture is depleted, (3) animal numbers and their distribution must be controlled to reduce browsing and trampling damage, and (4) costs of a grazing program must be minimized.

On young conifer plantations, maximum reductions in the plant vigor of understory vegetation can be achieved by reducing the carbohydrate reserves during periods of active growth. These reserves reach their lowest levels shortly after plants initiate shoot elongation. When grazing corresponds to this period, plant vigor and carbohydrate reserves of competing vegetation can be substantially reduced. Controlled grazing by domestic livestock on conifer plantations has had widespread applications in the last few years.

METHODS AND CASE HISTORY

Phase I (1977-85)

The study area resulted from a man-caused fire which occurred in 1977 known as the Piney Burn. It encompasses an area of 145 ha on the Defiance Plateau approximately 6 km southwest of Sawmill, Apache County, Arizona at an elevation of 2485 m. A salvage cut was conducted in the fall of that year to recover harvestable but damaged timber. In late spring, a large portion of the

burn was fenced and containerized Ponderosa pine seedlings were planted at a rate of 1683 seedlings per ha. Later that season, concern over surface erosion precipitated a decision to aerially seed adapted exotic and native grasses onto the burn. The results of that seeding were unusually successful to the extent that the subsequent failure of the reforestation project was attributed to grass-forb competition. The surface was later disked to prepare the seedbed for other plantings in 1981-2. A second planting of containerized seedlings was completed during that period, with the largest segment (100 ha) being planted in August, 1981. In each of the next three successive growing seasons, surveys were performed to monitor survival. The 1984 survey indicated that various environmental stresses were inhibiting Ponderosa pine seedling growth and reducing survival (Thomas 1986). The primary stressor identified by the survey was the high level of competing vegetative ground cover. Approximately 67 percent of the reforested area was covered by competing vegetation consisting mostly of exotic and native grasses. Management alternatives initially considered to reduce this competitive effect were prescribed grazing, manual scalping and herbicide applications.

In the spring of 1985, twelve (12) 0.025 ha plots were situated on the plantation at random coordinates. Each replication contained four subplots (0.00625 ha) measuring 15.8 X 15.8 m. The configuration of subplots within each replication was determined by a randomized block design. Treatments applied to each plot were as follows:

- (1) Untreated.
- (2) Manual scalping. Surface vegetation within a 0.6 m radius of seedling was removed using hand tools.
- (3) Herbicide (low intensity). Surface vegetation within a 0.6 m radius of pine seedlings was sprayed with Velpar L at a rate of 5 liters + 1450 liters water + surfactant (detergent)/ha.
- (4) Herbicide (high intensity). Surface vegetation within a 0.6 m radius of pine seedlings was sprayed with Velpar L at a rate of 10 liters + 1450 liters water + surfactant/ha.

Seven seedlings in each subplot were selected for measurement by rotating a tape from the center and marking the first seedling encountered at each 51 degree interval. Included in the collected data were density/subplot, mortality/subplot, cover by competing vegetation and growth parameters (height and stem diameter) of the selected seedlings.

Data were subjected to comparative analysis via the Anova 9 program modified for use on the Burroughs B21.4 computer. When the analysis of variance indicated F-values with significant levels of difference among means ($P < 0.05$), Duncan's Multiple Range Test was employed.

Concurrently, grazing trials were conducted within two (2) 0.8 ha enclosures measuring 90 X 90 m. Livestock were confined by solar-powered electrical fence for two periods of 24-30 animal



Figure 2.--Heavy grazing in enclosures (right of photo) suppressed vegetative understory with minimal damage to pine seedlings.

days in order to obtain a heavy level of utilization. Twenty-eight (28) seedlings were selected for monitoring in each enclosure by rotating clockwise a tape stretched due north from points on a systematic grid. Data collected from these plots were the same as for the defoliation plots but direct comparisons were not made because of inherent design differences.

Phase II (1986-1989)

The Piney Burn plantation with approximately 70 percent evenly distributed survival, was certified successful in 1986. In that year, a decision was made to expand the grazing trials to include the entire plantation. The 145 ha area was divided into three pastures by electrical interior fences. The three treatments were as follows:

- (1) Ungrazed by domestic livestock.
- (2) Moderately grazed in alternative growing seasons (1987 and 1989).
- (3) Moderately grazed in consecutive growing seasons.

Moderate grazing was considered to be utilization less than 50 percent of the above ground biomass, excluding wood species. That level of use was consistent with the work of earlier researchers (Currie 1975; Clary 1975) who recommended that 30 to 40 percent utilization and 30 to 38 percent utilization, respectively, were the optimum levels of use for Ponderosa pine-bunchgrass ranges. They suggested that levels of use greater than 50 percent could result in reduced animal production and potentially long

³ Logistical problems occurred in 1988 and prevented placement of cattle into the plantation. Therefore, this subunit was grazed in 1986, 1987 and 1989, but not in 1988.

Table 1. Vegetative cover in percent (%) during 1985 growing season in twelve (12) measured plots.

Treatment	Before Treatment	After Treatment		
	May 16	June 19	July 31	Sept. 23
Untreated	72.5 ^a	73.8 ^a	76.3 ^a	77.1 ^a
Manual Scalping	71.9 ^a	60.4 ^b	61.7 ^c	64.2 ^b
Herbicide (low rate)	70.8 ^a	69.6 ^a	73.8 ^{ab}	74.2 ^a
Herbicide (high rate)	70.8 ^a	68.8 ^a	70.0 ^b	72.9 ^a

^{a,b,c} Within columns, mean values followed by the same superscript are not significantly different ($P \leq 0.05$).

term damage to the range. Use levels were closely monitored each summer until the approximately 40 cattle introduced to the units had achieved desired levels of consumption. Data collection was deferred until Fall, 1989. Since the plantings had been made in three stages, the data collection was limited to the largest segment (100 ha planted in August, 1981) to eliminate possible differences resulting from age.

Within each of the three treatments, ten 100 m line transects were established at random coordinates. At the terminus of each transect, a 15 X 20 m quadrat was situated. Data collected at each site were as follows:

- canopy intersect (cover)
- density
- basal diameters
- heights.

Canopy intersect was obtained by measuring the aerial cover of Ponderosa pine over a 100 m tape; all seedlings rooted within the quadrats were counted and measured to determine density, diameter and height. Analysis of variance was not

performed on these data because the treatments were not replicated. Mean values, however, were tested using Duncan's Multiple Range Test.

RESULTS AND DISCUSSION

Phase I

Understory vegetation growing in subplots was significantly decreased by manual scalping ($P \leq 0.05$) but not by either level of herbicide application. The high rate of herbicide produced a temporary reduction in ground cover which was not sustained by season's end. The low rate of herbicide application did not produce either temporary or sustained reductions in vegetative cover. These results are displayed in Table 1.

Although the mechanical technique effectively reduced vegetative cover temporarily, it was extremely labor intensive and costly. Larson and Schubert (1969) have advised that Ponderosa pine should only be planted on completely grass-free areas. Complete site preparation involving killing or removing grasses was seen as the best

Table 2. Growth parameter increases in percent (%) during 1985 growing season on twelve (12) measured plots.

Treatment	Stem Diameter	Height
Untreated	+9.9 ^a	+16.1 ^a
Manual Scalping	+16.2 ^b	+20.1 ^b
Herbicide (low rate)	+16.2 ^b	+16.3 ^a
Herbicide (high rate)	+16.0 ^b	+16.8 ^a

^{a,b} Within columns, mean values followed by the same superscript are not significantly different ($P \leq 0.05$).

Table 3. Vegetative cover in percent (%) in two grazing enclosures during 1985 growing season.

Enclosure	Before Grazing	After First Grazing Cycle	After Second Grazing Cycle	End of Growing Season
Unit 1	70.2 ^a	65.3 ^b	59.5 ^c	61.1 ^c
Unit 2	69.9 ^a	66.8 ^{ab}	64.8 ^b	64.8 ^b

^{a,b,c} Within rows, mean values followed by the same superscript are not significantly different ($P < 0.05$).

condition for the survival and growth. Partial site preparation was considered to be inadequate and not suitable for Southwestern plantations.

The growth parameters of Ponderosa pine seedlings were affected by defoliation treatments. Manual scalping and both levels of herbicide application produced significantly greater ($P < 0.05$) increases in basal diameter. Manual scalping, however, was the only treatment producing greater height (Table 2).

In the two grazing enclosures, vegetative cover was significantly reduced ($P < 0.05$) after two grazing periods (Table 3). No grazing damage to pine seedlings was observed in spite of concentrated, heavy utilization of the grass-forb understory. Some trampling damage to seedlings did occur when cattle were left overlong in the enclosures but damage was light to moderate and within acceptable levels. Seedling mortality in the enclosures was very low. Mortality rates, based on total seedlings/unit, were 1.28 percent and 1.01 percent in Units 1 and 2, respectively. Mortality, when it occurred, was primarily attributed to trampling and bedding.

Phase II

The data collected in October, 1989, on the three larger grazing units are shown in Table 4. The inability to incorporate replications of

treatments in these trials disallows inferences about direct results of grazing. There are, however, certain trends indicated by the data.

The data do not indicate differences in density of seedlings between treatments. This suggests that grazing by cattle has not resulted in increased pine mortality. The highest cover (canopy) values were found in the treatment receiving the most frequent grazing use. The highest values for growth parameters, both height and basal diameter, were also found in the unit receiving the most intensive treatment.

These results are consistent with other recent studies which have employed livestock as biological agents to reduce competitive understory. In California, cattle graze mixed conifer plantations each year during the June 1-September 30 period (Kosco and Bartoleme 1983). Grazing treatments on clearcuts indicate that cattle do not harm tree regeneration on these plantations. No trampling damage was reported and browsing did not make any differences in overall tree seedling height or basal diameter between treatments. Sharrow et al. (1989) report that sheep grazing in the Pacific Northwest successfully suppressed competing vegetation on conifer plantations. The reduced understory biomass on grazed plantations was consistently associated with greater ($P < 0.05$) diameter growth of Douglas fir seedlings. Three

Table 4. Mean values on three grazing units after four years of treatment (1989).

Treatment	Cover (%)	Density No./Plot	Mean Height (cm)	Mean Diameter (mm)
Ungrazed	2.056 ^b	32.8 ^a	59.9 ^b	27.8 ^b
Grazed 2 of 4 years	1.200 ^b	25.6 ^a	55.2 ^b	26.0 ^b
Grazed 3 of 4 years	3.905 ^a	33.0 ^a	70.2 ^a	32.7 ^a

^{a,b,c} Within columns, mean values followed by the same superscript are not significantly different ($P < 0.05$).

seasons after the cessation of grazing treatments, trees in grazed plantations were approximately 5 percent taller ($P < 0.05$) and 7 percent greater ($P < 0.01$) in diameter (DBH) than trees in ungrazed controls. Pearson (1987) reported that 5 year old pines in Southern plantations were 1.5 feet taller on grazed vs. ungrazed sites. No significant differences in seedling survival were noted. On grazed vs. ungrazed plantations in eastern Oregon investigated by Krueger (1987), height growth of planted Ponderosa pine trees was 10 to 17 percent higher and diameters were 9 percent greater. In stands of Douglas fir in Oregon, Hall et al. (1959) reported that cattle effectively removed palatable grasses and reduced fire hazards without damage to the establishment and growth of tree seedlings. Finally, in Colorado, Currie et al. (1978) found that light to moderate stocking rates of cattle resulted in negligible damage to both artificial and natural regeneration in Ponderosa pine-bunchgrass ranges.

CONCLUSIONS

Established grass-forb understories can seriously suppress the establishment and growth of Ponderosa pine plantations. Such stands continue to inhibit conifer growth, primarily through competition for soil moisture, for many years after planting. Mechanical and chemical defoliation of the immediate understory can provide temporary advantages to pine seedlings but these applications are costly and labor intensive. Moreover, there is no available evidence that advantages to conifer seedlings are more than short-lived.

The most cost-effective strategy presently available for suppressing understory grasses and forbs is the use of livestock as biological agents. In the case study of Piney Burn, cattle were the biological agents employed. When utilization was restricted to a moderate level, cattle were introduced in the active growing season only and grazing was imposed annually, the following advantages were perceived:

- (1) Fire hazard was substantially reduced because available fuel was diminished.
- (2) Negligible mortalities of pine seedlings resulted from cattle activities.
- (3) A collateral use (grazing) of Ponderosa pine plantations was shown to be financially, as well as biologically, beneficial.
- (4) This and other reported studies indicate that grazing may enhance growth and development of conifer seedlings by suppressing competition.
- (5) The same physical facilities constructed to protect timber regeneration can facilitate controlled grazing by livestock.

LITERATURE CITED

Brock, John H. 1988. Livestock: Biological Control in Brush/Weed Management Programs. *Rangelands* 10:32-33.

- Clary, Warren P. 1975. Range Management and Its Ecological Basis in the Ponderosa Pine Type of Arizona: The Status of Our Knowledge. USDA Forest Service Research Paper RM-158. 35 p.
- Currie, Pat O. 1975. Grazing Management of Ponderosa Pine - Bunchgrass Ranges of the Central Rocky Mountains: The Status of Our Knowledge. USDA Forest Service Research Paper RM-159. 24 p.
- Currie, P. O., C. B. Edminister and F. William Knott. 1978. Effects of Cattle Grazing on Ponderosa Pine Vegetation in Central Colorado. USDA Forest Service Research Paper RM-201.
- Doescher, Paul S., Steven D. Tesch and Mabel Alejandro-Castro. 1987. Livestock Grazing: A Silvicultural Tool for Plantation Establishment. *J. Forestry* 85: 29-37.
- Hall, F. C., D. W. Hendrick and R. F. Keniston. 1959. Grazing and Douglas Fir Establishment in the Oregon White Oak Type. *J. Forestry* 57: 98-105.
- Hendrick, D. W. 1975. Grazing Mixed Conifer Clearcuts in Northeastern Oregon. *Rangeman's Journal* 2: 6-9.
- Kosco, Barbara H. and James W. Bartoleme. 1983. Effects of Cattle and Deer on Regenerating Mixed Conifer Clearcuts. *J. Range Management* 36: 265-268.
- Krueger, W. C. 1987. Pacific Northwest Forest Plantations and Livestock Grazing. *J. Forestry* 85: 30-31.
- Larson, M. M. and Gilbert H. Schubert. 1969. Root Competition Between Ponderosa Pine Seedlings and Grass. USDA Forest Service Research Paper RM-54. 12 p.
- Panter, Kip E. and Lynn F. James. 1987. A Review of Pine Needle and Broom Snakeweed Abortion in Cattle. p. 125-130. In *Proceedings-Symposium on Plant Herbivore Interactions*. USDA Forest Service General Technical Report INT-222.
- Pearson, Henry A. 1987. Southern Pine Plantations and Cattle Grazing. *J. Forestry* 85: 36-37.
- Sharrow, S. H., W. C. Leininger and B. Rhodes. 1989. Sheep Grazing as a Silvicultural Tool to Suppress Brush. *J. Range Management* 42: 2-4.
- Thomas, Stephen D. 1986. Piney Burn Conifer Release Study Report. Bureau of Indian Affairs, Branch of Forestry (Unpublished).
- Wood, G. M. 1987. Animals for Biological Brush Control. *Agronomy J.* 79: 319-321.

Effects of Prescribed Springtime Underburning on Production and Nutrient Status of a Young Ponderosa Pine Stand¹

Charles C. Grier²

Abstract.--The effects of prescribed fuel-reduction fire were examined experimentally in a 43-year-old *Pinus ponderosa* Laws. stand in north central Washington State. The stand had been precommercially thinned 14 years before this study. Competitive mortality indicated residual trees had fully reoccupied the site. Treatments were: unburned control, light burn (existing fuel load of $\approx 30 \text{ Mg ha}^{-1}$) and heavy burn (fuel added to total 85 Mg ha^{-1}). Relative to before-fire values, pine fine root biomass ($<2 \text{ mm}$ diameter) in the top 5 cm of soil had increased 50% on the control plots, stayed the same on the light burn plots and decreased 63% on the heavy burn plots when measured two weeks after the fire. Needle litterfall in the control plot during the year after burning was 0.66 Mg ha^{-1} while that on the light and heavily burned plots was 2.1 and 2.2 times control plot values. The amount of nitrogen and phosphorus returned in litterfall was 2- and 3-times control amounts on the light and heavy burn plots. Wood biomass increment of the burned plots was consistently about 10% greater than control before the fire. The year after burning, the light and heavy burn plots had wood biomass increment 66% and 52% of control values. Spring burning occurs when roots of trees are adapted to cold soils. Heat from fires was measurable at 10 cm and may have brought soil temperatures above the lethal temperatures for cold-adapted roots. Root mortality appears to have caused the observed changes in production and nutrient status.

INTRODUCTION

Relatively little is known about the fine root component of most forest ecosystems--even less is known of the impact of various forest management practices on this critical ecosystem component. There is no question that fine roots are an important part of an ecosystem; their role in water and nutrient uptake has long been well documented (Kramer and Kozlowski 1960). What is not generally appreciated is the investment a forest makes in maintaining its root system.

Previous studies in undisturbed forests have shown that fine root growth comprises a relatively large proportion of total forest productivity. Current estimates are that from 10% to over 70% of annual net primary production is utilized in maintaining the fine root system

of forests (Harris et al. 1978, Persson 1978, Keyes and Grier 1981, Vogt et al. 1986). Factors influencing production and turnover of fine roots are not yet completely understood but the proportion of annual net production utilized for fine roots appears to be inversely related to site quality. Keyes and Grier (1981) studied fine roots dynamics in young Douglas-fir stands growing on contrasting sites. On a productive site, only 15% of net production was used to produce fine roots--for poor sites about 40% of net production was utilized for fine roots. In well-watered, highly productive coastal forests of Oregon, only about 10% of annual productivity is invested in fine root growth (Grier et al. 1986). Moreover, the amount of fine roots produced annually appears to increase as site productivity decreases. In productive western coastal forests, fine root production is about 2000 kg/ha/yr (Vogt et al. 1986) while comparable values for poor site Douglas-fir and low productivity subalpine forests are about 7000 and $10,000 \text{ kg/ha/yr}$, respectively (Vogt et al. 1986).

Fine roots also play an important role in nutrient cycling. In addition to their role in

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²Charles C. Grier is a Professor, School of Forestry, Northern Arizona University, Flagstaff.

nutrient uptake, a substantial part of the ecosystem nutrient capital is invested in fine roots. For example, roughly 10% of the total nitrogen capital in the living part of a 30-year-old western hemlock stand on the Oregon coast was in the fine roots (Grier, 1976). Comparable values for poor-site Douglas-fir and low productivity subalpine silver fir stands are about 35% and 50% respectively (Keyes and Grier 1981, Grier et al. 1981).

Fine roots in most coniferous forests studied appear to be concentrated near the soil surface. In most coniferous forests where vertical distribution of fine roots has been quantified, over 80% of their biomass is shown to be in the upper 10 cm of soil. Of this 80%, about 60% to 70% is found in the upper 2-4 cm (Vogt et al. 1986). Thus, fine roots, which represent a significant portion of annual production and stand nutrient capital, are located in a position where they are vulnerable to a variety of forest management practices.

In Spring of 1979 I began a study of the effects of early-season fuel-reduction underburning on primary production and nutrient cycling in 45-year-old ponderosa pine stands. The basic premise was that, while ponderosa pine is a fire-adapted tree species, it is adapted to fires occurring late in the growing season, at least in the Intermountain region. Early season fires would occur when active root growth was in progress: heat conducted into the soil from early season fires would have the potential to damage or kill activity growing fine roots, consequently reducing productivity. These heat effects would be amplified by the high thermal diffusivity of moist soils and the low soil temperatures to which roots are adapted after winter. Late summer or early fall fires, on the other hand, occur when roots are inactive, soils are dry and thus good insulators, and roots are adapted to higher soil temperatures.

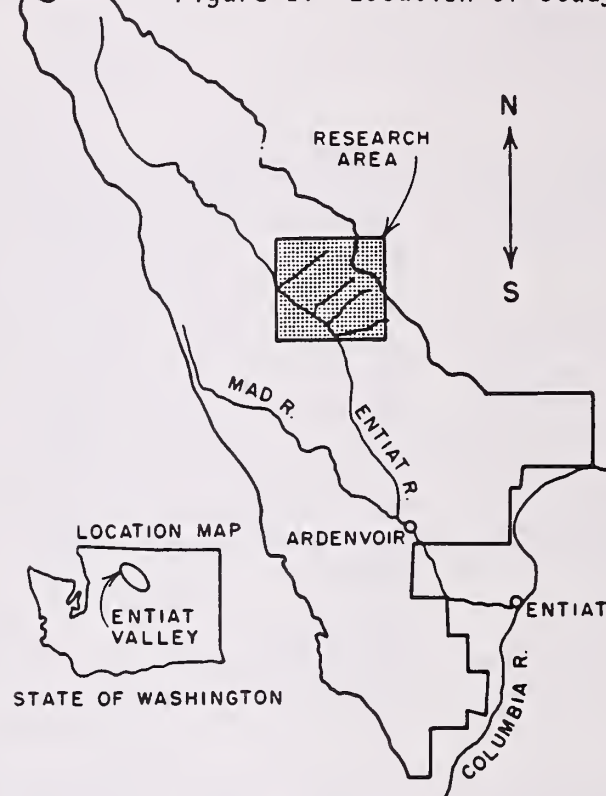
The objective of the research described in this paper was to investigate the possibility of fine root mortality occurring as a result of spring underburning in ponderosa pine stands on the east slope of the Washington Cascade Mountains. Specific objectives of the study were to: 1) determine the amount of fine root mortality resulting from fires in average and heavy fuels; 2) determine the changes in productivity, if any, resulting from fire-caused root mortality, and 3) determine the changes in nutrient distribution in stands subjected to underburning.

Results of this study should provide answers to questions regarding the influence of underburning on forest productivity. Moreover, information obtained from his research should enable the forest manager to use residue reduction fires in such a way as to minimize both short-term losses in forest productivity and the potential for invasions by root pathogens.

RESEARCH AREA

The study was conducted in a ponderosa pine stand located at Johnson Creek Summit, Entiat Ranger District, Wenatchee National Forest (Fig. 1).

Figure 1.--Location of study area.



The area is located in Section 6, T26N, R21E; Section 25, T27N, R20E and Sections 30 and 31, T27N, R21E, Willamette Meridian. The stand was about 45-years old at the time of burning in 1979. The stand had been precommercially thinned in 1967 to about 500 stems per hectare. Slash was lopped and scattered. Vegetation consisted of a dominantly ponderosa pine (*Pinus ponderosa* Laws.) overstory containing scattered Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) with a mixed grass-sedge understory. Stand characteristics are given in Table 1. Soils in the study area were Inceptisols formed in Swankane gneiss overlain by 10 to 20 cm of Glacier Peak volcanic ash (Wilcox 1965). The site is nearly level with an average annual precipitation of about 50 cm. July temperatures average about 18°C while January temperatures averaged -1°C.

The 50 m square plots were established in: 1) an unburned control area, 2) a light fuel burn plot representative of the average fuel loading in the area of 30 metric tonnes/hectare, 3) a heavy fuel burn plot in which fuel was added to approximate areas of heavy slash accumulation (85 t/ha) over the entire plot.

Burning was conducted on May 29, 1989. Burning was prescribed by and conducted under the supervision of Charles Wolf, Fire Management Officer, Entiat Ranger District, Wenatchee National Forest. The burning objective was to

Table 1.--Characteristics of research stand,
Johnson Creek Summit, Entiat R.D.,
Wenatchee N.F.

Species:	PIPO - PSME
Location:	Johnson Cr. Entiat R.D.
Elevation (m.):	930
Density (stems ha ⁻¹)	450
Basal area (m ² ha ⁻¹)	
1967	11.9
1979	19.7
1987	25.0
BAI (m ² ha ⁻¹) year ⁻¹)	0.4
Age (yr.)	58
Fuel load (tonnes ha ⁻¹)	
Thinning slash	11.2 - 78.4
Forest Floor	22.4
Prescribed burn	29 May 1979

achieve a fuel loading of "MM" over the study area.

METHODS

Burning was conducted by USFS personnel. Two intensities of fire were examined, intensity here being defined in terms of fuel loading. The light burn was conducted at the existing fuel loading (Table 1) while the heavy burn had fuel such as branches and foliage added to equal a loading of about 95 to T/ha.

A vegetation survey utilizing methods described by Daubenmire (1968) was conducted to assure that plots were representative of the overall forest type.

Sampling of the fine roots was conducted immediately before the burn and immediately after the burn. A total of 12 - 4 cm diameter, randomly located soil cores were taken to a depth of 15 cm from each plot at each sampling. In practice, this gave an estimate of live fine root biomass of $\pm 15\%$ at the 90% confidence level. Local fire severity at each sampling location was noted to aid in stratifying samples if necessary.

Fine roots were separated in the laboratory into those from the upper 5 cm of each soil core and those from 5 to 15 cm; this was done to facilitate detecting any mortality response to surface heat. Roots from all samples were additionally separated into the 0-2 mm, 2-5 mm, and >5 mm. size classes. All roots were dried at 70°C for 48 hours, then weighed. Weights were corrected for adhering soil particles by ashing samples of dried roots in a muffle furnace and computing a correction factor which was applied to the dry weights to compute biomass.

Diameters of all trees in each plot were measured to the nearest 0.1 cm. Increment cores were taken from each tree in fall of the year of burning. These data plus those from litterfall measurements were used to estimate above ground.

Productivity changes were estimated from annual litterfall collections (dry wt. - 70°C) and growth ring analysis. In the latter case stand biomass increment was calculated using published biomass regressions on stem diameter for ponderosa pine (Gholz et al. 1979).

Eight, 0.25 m² litter screens were installed on each plot. Samples were collected one month after the burn and every six months through 1982. Samples were sorted into two categories: foliage and other material. We anticipated increased leaf litterfall as a result of fire. This procedure provided a simple measure of its magnitude.

Soil samples were obtained from soil cores after the live roots were removed. Each sample was a composite of four samples from the two root sampling layers. Roots were also sampled and bulked to give 3 samples per horizon for each plot. These samples were used for determinations of percent ash, N and P. This part of the study (not yet completed) will aid in detecting changes in nutrient availability. Current years and older foliage, current years twigs, branches, stemwood, stembark and litter samples were also subjected to chemical analysis. Details of analysis are given by Grier 1976.

Heat sensors were constructed from Templog® paints and Tempilstik® crayons on asbestos sheet. These were installed at the soil surface and at 2.5 cm and 10 cm below the surface to determine the soil temperature profile beneath each burn. Twenty sensors were used at each level on each treatment. Sensors covered the temperature range from 40°C to 200°C in roughly 20°C intervals. Additional temperature measurements were made during burning at the 10 cm depth using a recently calibrated dial thermometer to measure temperatures.

RESULTS AND DISCUSSION

The prescribed fire effectively reduced fuel loadings in the study stand. Table 2 shows the reduction in surface fuels resulting from the fire.

In addition to the 70 to 90% reduction in forest floor and thinning slash, stumps remaining from the pre-commercial thinning were also burned. Burning raised temperatures in soils of the treatment plots (Table 3) even at the 10 cm depth.

Soils were near field moisture capacity at the time of burning. For this reason, thermal diffusivity of the soils was high and

Table 2.--Pre- and post-fire surface fuel loads for Johnson Creek Summit study plots.

<u>Pre-Burn (T ha⁻¹)</u>		
<u>Control</u>	<u>Light</u>	<u>Heavy</u>
33.6	33.6	93.2
<u>Post-Burn (T ha⁻¹)</u>		
33.6	10.1	6.7
<u>Fuel Reduction (%)</u>		
0	70.0	92.9

evaporative cooling at the surface probably reduced soil heating. Temperatures measured here were low relative to those measured in many other prescribed fires (Grier 1972). However, increased temperatures were observed deeper in the soil profile than when soils were drier (Grier 1972).

In spite of relatively low soil temperatures, burning caused measurable change in fine root production in the treatment plots. Figure 2

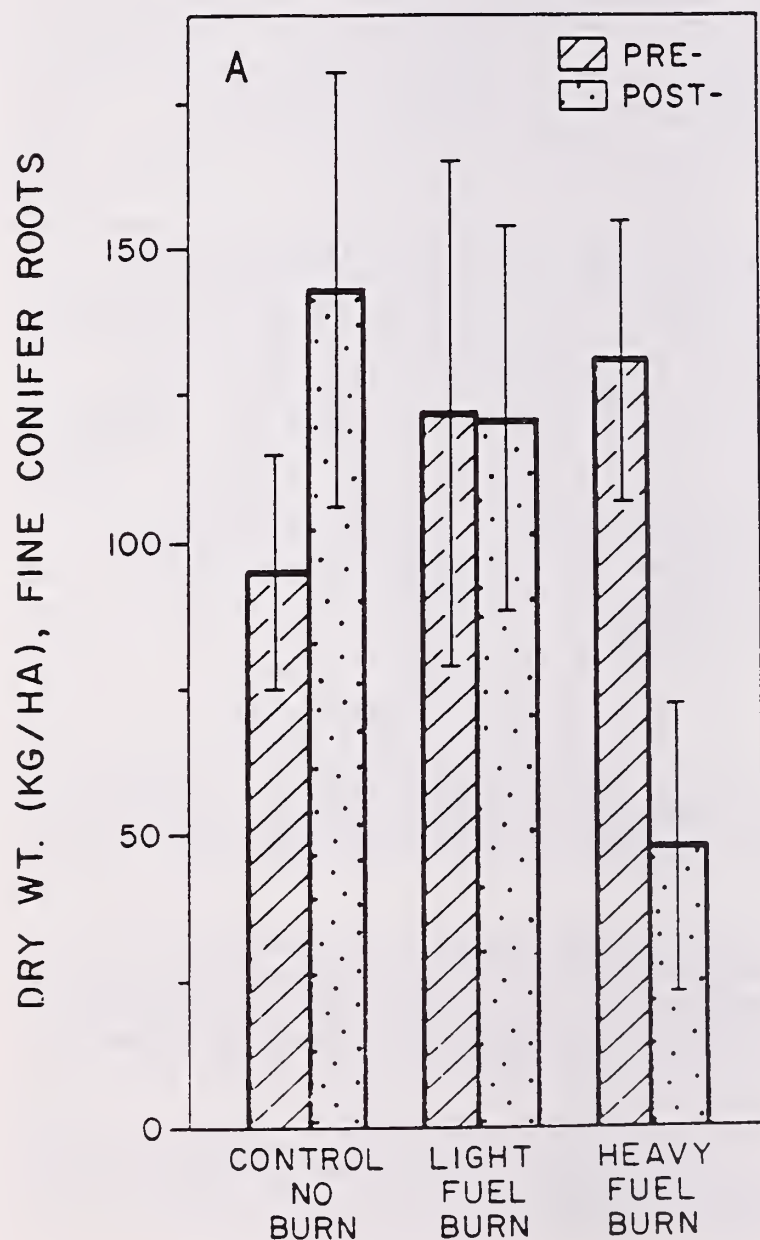


Table 3.--Peak temperatures (°C) reached in soils of treatment plots during fuel-reduction underburn. Johnson Creek Summit study plots Entiat R.D., Wenatchee National Forest.

Depth (cm)	Control 1/	Light Fuel	Heavy Fuel
0	8	60 2/	180 2/
2.5	6	40 2/	100 2/
10.0	5	20 3/	40 3/

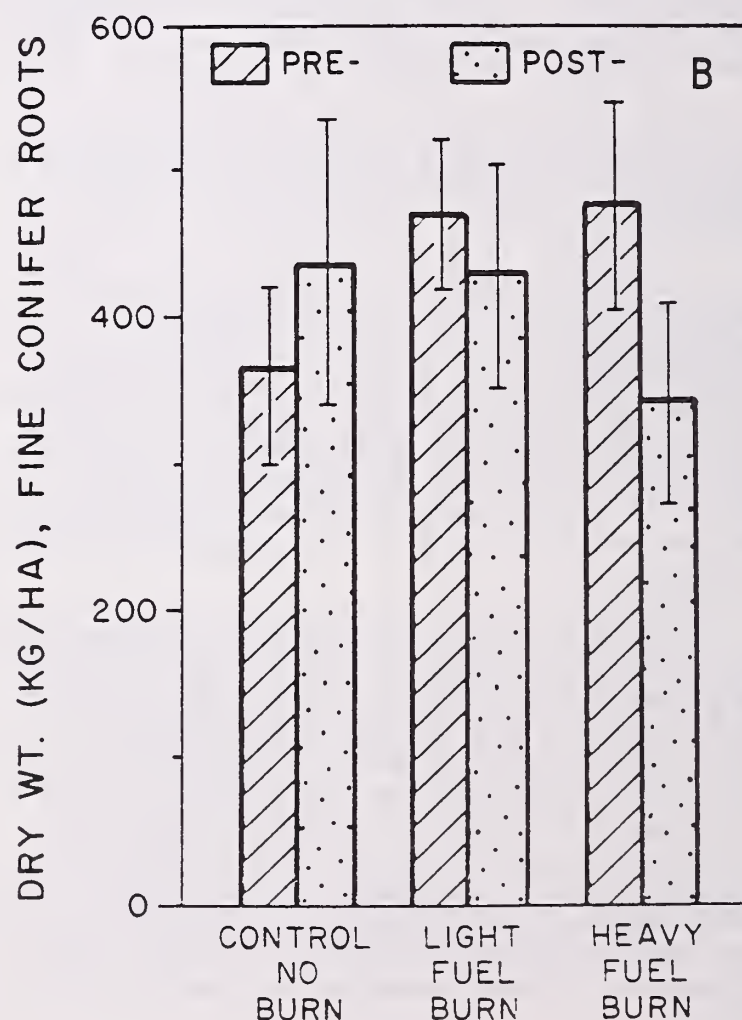
1/ Measured at noon 28 May 79

2/ Peak temperatures during fire were measured using Tempac® and Tempilstik®. Temperatures were greater than values listed, but below the next step. Steps were about 20°C apart.

3/ Measured with dial thermometer about 10 min. after the flame front had passed, 6 locations per treatment.

shows pre- and post-burn fine root biomass of ponderosa pine in the 0 to 5 cm, and 5 to 15 cm layers of root biomass in the plot.

Figure 2.--Effect of burning on fine root biomass in Johnson Creek Summit study plots. A shows changes near surface while B shows changes deeper in profile.



Control plot fine root biomass increased over the interval between samplings. This increase was probably the normal spring flush of fine root growth. In contrast, fine roots in the light fuel burn showed essentially no change between samplings, while there was a 60% reduction in live fine root biomass in the interval in the heavy fuel burn. Reduced surface root production in the light fuel burn probably resulted from either heat injury to roots or the release of nutrients from the ash layer reducing the need for root growth. Fertilization has been shown to reduce root production in Douglas-fir (Grier et al. 1986) and the same response probably occurs in ponderosa pine. Reduction in fine root biomass in the heavy fuel burn is almost certainly due to heat injury.

The same trends in fine root biomass are apparent in the 5 to 15 cm layer of soil (Fig. 2) though they are somewhat muted by distance from the source of heat.

Figure 3 shows stemwood biomass increment for four growing seasons including 1979, the year of burning.

It is apparent that 1979 was a poor growth year for all treatments but reduction in growth as a percent of the mean for the three previous years, was much more severe for the burned plots (light fuel - 50% reduction, heavy fuel - 66%) than for the unburned plots (29%). The biomass increment reduction in the light fuel burn tends to rule out nutrient release as a factor in the suppression of root growth noted on these plots. Reduced root production in response to fertilization is generally accompanied by increased wood production (Grier et al. 1986). Trees in the heavy fuel burn went from most productive to least productive of the three areas.

Needle litterfall on treatment plots was more than twice that on control plots (Table 4). On the light burn plot, this was probably due to the reduction in fine root biomass available to support a given level of foliage biomass. This, together with heat scorching of the foliage most likely caused foliage loss on the heavy fuel plots.

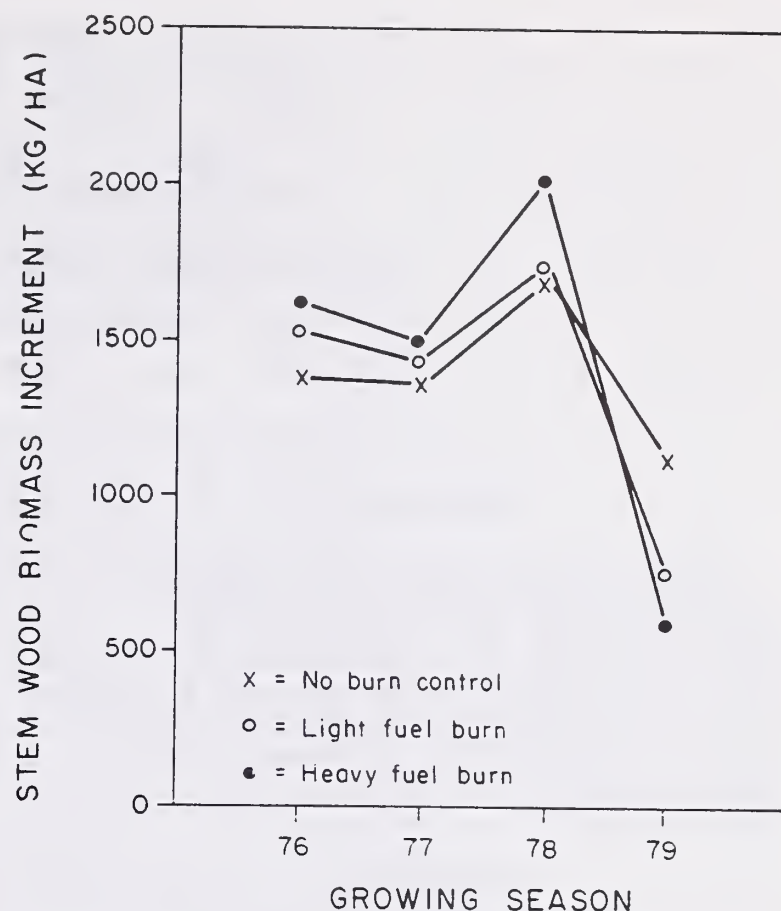


Figure 3.--Biomass increment on Johnson Creek Summit study plots after burning.

Concentration of nitrogen in needle litterfall from the burned areas was greater (5% in light fuels, 32% in heavy fuels) than in the unburned (Table 4). Trees in the burned plots thus lost more nitrogen (more than twice as much in the light fuel, almost three times as much in the heavy fuel) than in the unburned. Losses above those normally found in needle litter will have to be recouped before the stands in the burned areas can resume their pre-burn rates of production. Since both foliage and fine root biomass appear to have been set back, it seems reasonable to postulate further reduced production of stemwood increment for the next several years as photosynthate and nutrients are diverted to replacing lost foliage and roots. In fact, wood increment on the treatment plots was still below that of control plots eight years after burning (Table 5).

Table.4--Litterfall and litterfall nitrogen content from first year after burning on Johnson Creek Summit burn plots, Entiat R.D., Wenatchee National Forest.

	Needle litterfall kg/ha ⁻¹	N %	N in needle litterfall, kg/ha ⁻¹	N ratio (% of unburned)
Unburned	660	.393	2.58	1.00
Light fuel burn	1380	.414	5.70	2.21
Heavy fuel burn	1470	.520	7.64	2.96

Table 5.--Biomass increment (kg ha^{-1}) on Johnson Creek Summit fire plots: the 4-year pre-burn average, the year of burning for 1980 through 1987.

	(Burn) 1979	Avg. 74-78	1979 as % of 74-78	Avg. 70-98	80-87 as % of 74-78
Control	1370	1920	71.4	1800	93.8
Light fuel	910	1830	49.7	1640	89.6
Heavy fuel	710	2090	34.0	1390	66.5

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LITERATURE CITED

- Daubenmire, R. 1968. Plant communities: a textbook of plant synecology. Harper and Row, New York. 300 p.
- Gholz, H.L., C.C. Grier, A.G. Campbell and A.T. Brown, 1979. Equations and their use for estimating biomass and leaf area of Pacific Northwest trees, shrubs and herbs. Oregon State University, Forestry Research Lab Paper No. 1304. Corvallis, OR.
- Grier, C.C. 1972. Effects of fire on the movement and distribution of elements within a forest ecosystem. Ph.D. dissert. Univ. Wash. Seattle. 167 p.
- Grier, C.C. 1976. Biomass, productivity and N and P cycles in hemlock-spruce stands of the central Oregon Coast. p. 71-81. In Atkinson, W. and R.J. Zasoski (Eds.) Western Hemlock Mgt. Institute of Forest Resources Contrib. 34. Univ. Wash. Seattle.
- Grier, C.C., K.A. Vogt, M.R. Keyes, and R.L. Edmonds. 1981. Biomass distribution and above- and below-ground production in young and mature *Abies amabilis* ecosystems of the Washington Cascades. Can. J. For. Res. 11:155-167.
- Grier, C.C., T.M. Hinckley, K.A. Vogt, and S.T. Gower. 1986. Net primary production in Douglas-fir ecosystems: Its relation to moisture and mineral nutrition. p. 155-161. In Oliver, C.D., D.P. Hanley, and J.A. Johnson (eds.) Douglas-fir: Stand management for the future. University of Washington, Institute of Forest Resources, Contribution No. 55.
- Harris, W.F., R.S. Kinerson, Jr. and N.T. Edwards. 1978. Comparison of belowground biomass of natural deciduous forests and loblolly pine plantations. p. 29-37. In: Proceedings, The Belowground Ecosystem: A synthesis of plant-associated processes. J.K. Marshall (Ed.), Range Science Department Science Series No. 26, Colorado State University, Fort Collins, CO.
- Keyes, M.R. and C.C. Grier. 1981. Above and below-ground net production in 40-year-old Douglas-fir stands on low and high productivity sites. Can J. For. Res. 11:599-605.
- Kramer, P.J. and T.T. Kozlowski. 1960. Physiology of trees. McGraw-Hill, New York. 642 p.
- Persson, H. 1978. Root dynamics in a young Scots pine stand in Central Sweden. Oikos 30:508-519.
- Vogt, K.A., C.C. Grier and D.J. Vogt. 1986. Production, turnover, and nutrient dynamics of above- and belowground detritus of world forests. Adv. Ecol. Res. 15:303-377.
- Wilcox, R.E. 1965. Volcanic ash chronology p. 807-816. In: The Quaternary of the United States. Wright, H.E. and D.G. Grey (Eds.). Princeton Univ. Press, Princeton, N.J.

***In Vitro* Culture of Ponderosa Pine: Current Status and Future Prospects¹**

Yiqun Lin² and Michael R. Wagner³

Abstract.--The current status of knowledge about ponderosa pine (*Pinus ponderosa* Dougl. ex Law.) *in vitro* culture techniques for both juvenile and mature trees is presented. *In vitro* culture of ponderosa pine is at a very early stage of development compared with other gymnosperm species. Basic research on topics such as the mechanism of growth regulator effects on morphogenesis of cultures has received much less attention in ponderosa pine compared to other gymnosperms. Some techniques such as cell suspension culture and protoplast culture have not been applied to ponderosa pine. By devoting more effort to fundamental work and methods of *in vitro* culture, progress on ponderosa pine tissue culture will be greatly accelerated. We discuss the potential values and broad application prospects of *in vitro* culture in tree improvement programs of ponderosa pine.

INTRODUCTION

In vitro culture is defined as "the culture on nutrient media under sterile conditions, of plants, seeds, embryos, organs, explants, tissues, cells and protoplasts of higher plants" (Pierik 1987a). It is composed of the following techniques: 1) embryo culture, 2) organ culture, 3) cell suspension culture, 4) callus culture, and 5) protoplast culture. *In vitro* culture activities started in 1902 (Haberlandt 1902). The idea of *in vitro* culture started as a research tool to study factors affecting cell division and cell differentiation. *In vitro* culture technology served basic research for several decades. Not until the 1950's were *in vitro* culture techniques applied to agriculture and horticulture. With the rapid development of techniques and successful application to agriculture and horticulture, forest breeders and

forest geneticists have been greatly attracted by *in vitro* culture techniques. Various woody species including angiosperms and gymnosperms have been propagated by *in vitro* culture techniques. These techniques for woody plants have proven to be of great value in mass propagation. Commercial production of several angiosperm species has been highly successful, such as *Eucalyptus* and *Populus*. It is reported that 100,000 plants may be produced from a single terminal bud of mature *Eucalyptus citriodora* Hook (cited by Haissig et al. 1987). In gymnosperms, more than 10 species have successfully produced plantlets. Among these species, *Sequoia sempervirens* (Lamb.) Engl. (Boulay 1987) and *Pinus radiata* D. Don. (Horgan 1987) have been commercially propagated.

The value of *in vitro* culture has not only been proven in mass propagation, but it has also been recognized as a tool in tree improvement programs. Its advantages compared with conventional breeding methods have been generalized as follows:

- 1) reducing the time of a breeding cycle;
- 2) rapidly increasing the number of propagules in a given time;
- 3) overcoming natural genetic barriers during the process of crosses;
- 4) conserving the gene pool and modifying germplasm.

For instance, Aitken-Christie et al. (1988) reported that one embryo of radiata pine could

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²Yiqun Lin is a Graduate Research Assistant in the School of Forestry, Northern Arizona University, Flagstaff, Ariz.

³Michael R. Wagner is an Associate Professor, School of Forestry, Northern Arizona University, Flagstaff, Ariz.

produce 5,480 pieces of meristematic tissue in 13.5 months. Each piece of meristematic tissue formed an average of 68.4 shoots. They estimated that in 2.5 years, 260,000 trees could be produced from a single, healthy embryo (Aitken-Christie 1987). Likewise, the susceptibility or resistance to the blister rust disease in seedlings or mature trees of *Pinus lambertiana* Dougl. can be examined in vitro in only 14 days (Diner and Mott 1982); whereas a routine progeny test would take much more time and energy. The in vitro culture technique has been more and more appreciated by forest breeders and geneticists. However, in vitro culture of ponderosa pine has just recently been initiated. In this paper, the current status of in vitro culture of ponderosa pine, its limitations, its future prospects, as well as its potential application to ponderosa pine tree improvement are discussed.

HISTORICAL REVIEW

In vitro culture of ponderosa pine began in 1969 (Harvey and Grasham). They used stem cortex of 3-5 year old ponderosa pine seedlings as starting material. The callus was obtained from the cortex tissue by applying Indole-3-acetic acid (IAA), Naphthalene acetic acid (NAA) and 2,4-Dichlorophenoxyacetic acid (2,4-D) at concentrations of 100, 500, and 1000 $\mu\text{g/l}$. NAA (500 $\mu\text{g/l}$) resulted in the best yield of callus. Recently, Tuskan et al. (unpublished) successfully induced shoots from embryo culture of ponderosa pine. The effect of growth regulators, basal media formula and carbohydrate levels which affect the explants growth and development, were tested. Schenk-Hildebrandt (SH) basal medium (Schenk and Hildebrandt 1972) with 4.4 μM Benzylamino purine (BAP) + 5.4 μM NAA and 1 sucrose was determined to be the best treatment for callus initiation. Callus was best maintained in the Linsmaier-Skoog (LS) medium (Linsmaier and Skoog 1965) with 44.0 μM BAP + 5.4 μM NAA and 2% sucrose. The best result of shoot formation was achieved in the modified Gresshoff-Doy (GD) medium (Gresshoff and Doy 1972) containing 44.0 μM BAP + 0.054 μM NAA and 4% glucose. Ellis and Bilderback (1989) reported the multiple axillary buds were formed in vitro from cotyledons of ponderosa pine. They tested the effect of BAP on the competence of multiple axillary bud formation of cotyledons of ponderosa pine. It was found that the presence of BAP is necessary for axillary bud formation of ponderosa pine cotyledons. An investigation of the effect of nutrient constituents on bud production from embryos was also performed (Ellis & Bilderback 1983, Bilderback & Ellis 1985). They found that bud formation was higher on half strength Cheng media (Cheng 1975) than on full strength. It is also found that dilution of vitamin concentration in SH media resulted in increased formation of "incipient bud primordial." They concluded that inositol was "inhibitory to the induction of bud premo-

dial" and vitamins were not necessary for "bud and primordial induction."

In vitro culture of mature ponderosa pine has recently been initiated (Lin et al. unpublished). Axillary buds were induced from embryonic shoots without meristem tissue of mature ponderosa pine by initially using 1.0 mg/l 2,4-D + 0.5 mg/l BAP in MS media and 2 weeks later they were transferred into MS media with 1.0 mg/l BAP + 0.5 mg/l NAA. They found that different positions of explants on the trees significantly affected the formation of axillary buds. The explants located at the top of the trees formed more axillary buds than those from the lower crown of the trees. The season was also a critical factor for the axillary bud formation. The explants collected in winter never formed axillary buds but instead formed callus; whereas the explants collected in Autumn formed axillary buds, although small amount of explants produced callus. In another experiment, abundant callus tissue was obtained from needle explants of mature ponderosa pine by applying 1.0 mg/l 2,4-D + 0.5 mg/l BAP. By subsequently applying two subcultures of the callus tissue, tracheid mass with surrounding meristem tissue (vascular nodule) was observed from the callus after the second subculture. This indicated that callus derived from explants of mature ponderosa pines are capable of forming new tissue or organs. Gresshoff (1978) argued that the further development of vascular nodules in callus would lead to form "general premeridium" and eventually to form buds or roots. In addition, from the callus culture, embryogenic callus capable of forming somatic embryos during their further development was found after two weeks growing on the first subculture Murashige-Skoog (MS) media (Murashige and Skoog 1962) with 1.0 mg/l BAP + 0.5 mg/l NAA.

KNOWLEDGE GAPS IN IN VITRO CULTURE OF PONDEROSA PINE

It is encouraging to see that ponderosa pine tissue culture has achieved considerable success in a short period of time. However, in vitro culture of ponderosa pine has limitations and much less effort has been devoted to its study compared with other gymnosperm species. Previously, much less work has been done on some aspects which play an essential role in in vitro culture of plants. The limitations of in vitro culture of ponderosa pine could be categorized in the following aspects: 1) Basal nutrient media selection, 2) growth regulator effects and 3) development procedures of explants in the culture media. Without a better understanding of these aspects, the process of in vitro culture of ponderosa pine will be inhibited.

Basal Nutrient Media Selection

Media, containing various minerals, amino acids, vitamins, and carbon sources, is a basic

nutrient source for explant growth. Different plant species, different organs, tissues, and different physiological ages require different nutrient compositions and concentrations (Teasdale 1987). Therefore, determining the correct media formula for different target plant materials is very important. Several standard media formula have been developed in some angiosperm species. MS media was originated for tobacco tissue. Lepoivre (LP) media (Quoirin and Lepoivre 1977) was developed for *Prunus*. GD media was developed for tomato tissue culture. Now, modified GD and LP medium have been widely used in gymnosperm species (Lesney et al., 1988, Aitken-Christie et al., 1988, Thorpe 1988, Arnold and Hakman 1988). Ball (1987) reported that MS media, as a universal media, was less effective than Wolter-Skoog (WS) media (Wolter-Skoog 1966) for in vitro culture of *Sequoia*. In the previous work of ponderosa pine, modified GD was found to be the best media for shoot formation of cotyledons and SH media initiated callus formation from cotyledons (Tuskan et al., unpublished). Ellis and Bilderback (1989) used half strength of SH media to induce adventitious buds from cotyledons which were not separated from embryos. It is not surprising to find that the adventitious buds could be regenerated from the cotyledons of ponderosa pine by using different treatments by Ellis and Bilderback (1989 and Tuskan et al. unpublished). However, the mechanisms are not known.

For evaluating media formula, several aspects should be well understood: 1) metabolic requirements of micronutrients in target tissue in vitro and 2) interactions among different compounds in media.

Metabolic Requirements of Micronutrient of Target Tissue In Vitro

Different physiological states of tissues would require different levels of the same compounds. Mature foliage of pine needs a lower amount of copper (Cu) than juvenile foliage, and the requirement of manganese (Mn) is the reverse (Teasdale 1987). *Pinus radiata* seedlings require 64 μ M iron (Fe), whereas Douglas fir (*Pseudotsuga menziesii* [Mirb] Franco) embryo needs 27 μ M Fe (Teasdale 1987). Bilderback and Ellis (1985) reported that inositol inhibited bud primordia induction of ponderosa pine embryo explants. The role of inositol on the other explants of ponderosa pine is not known.

Interactions of Compounds

Phosphate and iron in a media usually precipitate (Teasdale 1987). In MS media, it is reported that "over half the Fe is in fact precipitated by phosphate" (cited in Teasdale 1987). This indicated that the "metabolic interaction effects can dramatically affect the availabilities of some micronutrients" (Teasdale 1987). Therefore, when modifying standard media, this factor should be considered.

After the above knowledge is obtained, it would be easier to evaluate media. It is suggested to determine proper media for explant growth, micronutrient compound thresholds of deficiency and toxicity in target tissue needs to be measured. The concentrations of specific compounds in the media has to fall between the thresholds. Detailed methods of how to determine the media formula is clearly discussed by Teasdale (1987).

Determining the Appropriate Combination of Growth Regulators

Growth regulators play a very important and complicated role in plant tissue culture. They affect explant growth in the following ways: 1) Auxin alone would induce callus or roots; 2) Auxin and cytokinin combination would cause callus, shoots or roots depending on different ratios of auxin to cytokinin; 3) cytokinin alone usually induces shoots (Minocha 1987). However, the responses of target materials to growth regulators are usually hard to predict. Minocha (1980) did not observe any shoot formation from callus derived from embryos of *Pinus strobus* L., although he tried more than 100 growth regulator combinations. The physiological response of target materials primarily depends on the types of explants and species. Some tissues or organs are exogenous auxin or cytokinin independent and some are highly dependent to exogenous growth regulators during their development. In addition, it also depends on interactions among growth regulators and interactions between growth regulators and chemical compounds (Pierik 1987b, Gresshoff 1978). For instance, Skoog (1971) found that exogenous cytokinin stimulated thiamin, auxin, and other cytokinin synthesis in tomato tissue culture. The conclusion that vitamins were not an absolute requirement for buds and primordia induction (Bilderback and Ellis 1985) may be due to the fact that BAP stimulated the vitamin synthesis in the cultured ponderosa pine embryos. Unfortunately, the basic questions of mechanisms have remained uninvestigated in in vitro culture of ponderosa pine.

Development Process of Cultured Explants

In the previous work with in vitro culture of ponderosa pine, study of the development process of cultured explants has been neglected. The study of development processes can provide us with very valuable data. It helps us to understand the correlations between morphogenesis, growth regulators, and micronutrient compounds which allows for the determination of suitable media formula and growth regulators (Gresshold 1978).

The initial process of morphogenesis usually cannot be seen without histological and histochemical techniques. By applying these methods, we will be able to trace the development of

callus tissue, and to determine if a treatment is correct. In our experiment, although we did not induce any shoots or roots from callus, we observed histogenesis by using histological methods (Lin et al., unpublished). This at least demonstrated that the callus derived from explants of mature trees have the ability to form new tissue, and one of the treatments was suitable for callus development providing us with a clue for further study in this aspect.

FUTURE PROSPECTS OF IN VITRO CULTURE OF PONDEROSA PINE AND ITS POTENTIAL APPLICATION IN TREE IMPROVEMENT PROGRAMS

Ponderosa pine is one of the most widely distributed species in the western United States. Its lumber production constituted one-third of the total lumber production in the inland western United States during 1986 (Van Hooser & Keegan 1988), and the timber is utilized in various ways by forest industries. The great demand for ponderosa pine results in harvest exceeding growth in some western states (Van Hooser & Keegan 1988). This harvest/growth imbalance might cause a shortage of ponderosa pine in the future (Van Hooser & Keegan 1988). To increase the production of ponderosa pine to meet the future demand, one major strategy would be to improve timber production by basic tree improvement methods.

As we mentioned previously, in vitro culture technology plays an ever-increasing role in tree improvement programs, especially for gymnosperm species. The main purpose of tree improvement programs is to obtain maximum genetic gain in a given time. In conventional ponderosa pine tree improvement programs, several major constraints exist: 1) long-time breeding cycle, 2) grafting incompatibility, and 3) rooting difficulty. Ponderosa pine usually reaches maturity at age 20-40. Because of their long juvenile phase, once an elite trait is found, the genetic gain in the next generation would not be obtained for at least 20 years. Some elite traits will not be expressed until tree reaches maturity. For instance, ponderosa pine resistant to some insects may be recognized only when the tree reaches maturity. In routine progeny tests, it may not be possible to detect the resistant trait of progeny for at least 20 years. Attempts at rooting cuttings from mature ponderosa pine, while successful, did not meet commercial expectations (Wagner unpublished). The best rooting frequency was 27% and the rooted cuttings tend to grow slowly (Wagner unpublished). By applying in vitro culture techniques, this problem hopefully would be resolved.

In vitro culture of ponderosa pine is in a very early stage. Much effort is required before this technique can be applied to tree improvement programs. To rapidly develop in vitro culture of ponderosa pine, research should focus on basic research into growth processes and methods of in vitro culture.

Basic Research

As we have discussed earlier, most attention has been given to how to manipulate growth regulator combinations. Some fundamental research such as determining media formula and the essential knowledge of growth regulator mechanism has not been investigated. The above limitation was not only found in in vitro culture of ponderosa pine, but also exists in most in vitro culture of gymnosperm species. The necessity and urgency of the above fundamental studies are apparent and has been brought up by many scientists (Minocha 1987, Teasdale 1987, Mehra-Palta and Thompson 1987). The fundamental research requires large scale scientific effort. It would involve biochemists, botanists, forest geneticists, and forest breeders. The history of in vitro culture tells us that fundamental work could take considerable time. For instance, potato tissue culture techniques required 30 years to be developed and now the techniques greatly benefit potato production (Slack 1988). *Sequoia sempervirens* tissue culture techniques required almost 30 years (Boulay 1987), but the results of these studies eventually resulted in mass propagation, and production of disease-free plants for the horticulture industry (Gresshoff 1978).

Accomplishing In Vitro Culture and Exploring Potential Applications

To date, in vitro culture of ponderosa pine is limited to the methods of embryo culture (Ellis & Bilderback 1989, Tuskan, unpublished), callus culture (Lin et al. unpublished), and axillary bud culture (Lin et al. unpublished). The system of in vitro culture of ponderosa pine has not been well developed. By applying other methods, the progress of in vitro culture of ponderosa pine might be accelerated and some genetic gain could be achieved in a tree improvement program in a short period of time.

Embryo Culture

Embryo culture is defined as "the sterile isolation and growth of an immature or mature embryo in vitro, with the goal of obtaining a viable plant" (Pierik 1987c); it has been demonstrated as a "reliable technique" for in vitro culture in gymnosperm species. Boulay (1987) indicated that embryo culture would increase the multiplication rate to 10-40 times higher than the multiplication rate by rooted cuttings for conifer species. It would be beneficial in the following situations: 1) when seed germination is poor; 2) when control pollination does not yield enough seed to meet reforestation need; 3) when interspecific and intraspecific crosses results in hybrids that yield poorly; and 4) to test species breeding criteria, such as resistance to diseases or pests prior to progeny tests.

Axillary Bud Culture

This is a method to obtain axillary buds in in vitro and subsequently to develop the buds into shoots, and eventually to obtain whole plantlets. This method could be applied to mass propagation of both juvenile and mature trees. It has been successfully applied in the multiplication of *Sequoia* (Boulay 1987) and loblolly pine (*Pinus taeda* L.) (Amerson et al. 1988). The "real benefit" of in vitro culture is the ability to propagate from mature trees because frequently it is impossible to determine the genetic potential from embryos or seedlings, unless there are juvenile-mature correlations (Bonga 1987, Mehra-Palta and Thompson 1987). We have developed a technique to obtain axillary buds from embryonic shoots of mature ponderosa pine (Lin et al. unpublished). This provides us with excellent starting material, since the axillary bud is a stable genetic base and has much less risk of variation than callus tissue within a generation (Pierik 1987d). Further effort to develop these axillary buds into shoots is needed in order to obtain plantlets. The continuous development of this technique could become an important tool in the asexual propagation of mature ponderosa pine.

Callus Culture and Cell Suspension Culture

Callus culture is a method in which mass of unorganized tissue, callus, is induced. The callus is then transferred into new medium in order to regenerate into organs or somatic embryos (Pierik 1987a). Cell suspension culture is defined as "cell and cell aggregates dispersed and growing in moving liquid medium" (Street 1977). Callus is often used as starting material in cell suspension culture.

Callus culture combined with cell suspension culture has been considered as a great potential tool to achieve regeneration from somatic embryos. Durzan calculated that 100,000 acres could be reforested with the plants which would be regenerated by embryogenesis from 100 liters of culture in only 3 months (cited by Aboel-Nil 1987). Cell suspension culture have yielded promising results in gymnosperm species recently. Out of 13 recent literature citations on embryogenesis, nine of them were applied cell suspension culture method (Attree et al. 1987, Boulay et al. 1988, Durzan and Gupta 1987, Gupta and Durzan 1987, Kartha et al. 1988, Krogstrup et al. 1988, Hakman and Fowke 1987, Hakman et al. 1985, Hakman and Arnold 1988). In ponderosa pine callus culture, it is encouraging to find embryonic cells which would be able to develop into somatic embryos in our callus culture. If cell suspension culture were applied, somatic embryos could have been produced.

Callus culture may have great value in mature tree propagation, since most mature trees could easily produce callus. It is also becoming

a very powerful tool for bioassay of genetic resistance to disease (Mott & Amerson 1984, Diner & Mott 1982). Mott and Amerson (1984) reported that the callus derived from embryos of *Pinus lambertiana* showed genetic resistance to

blister rust hyphae. This method could be applied to investigating ponderosa pine genetic resistance to insects. Since we have developed a method to obtain callus from needles of mature ponderosa pine, it may be possible to conduct a tissue culture bioassay of candidate resistance material. Callus culture can also be beneficial in gene pool conservation and the study of host-parasite interaction. One of the major tasks of tree improvement programs is to conserve germplasm for long term breeding programs (Zobel and Talbert 1984). In routine gene conservation of trees, large space is needed. By using in vitro culture technique, the germplasm could be stored in a limited space. This could be achieved by freezing tissues and callus. Zobel and Talbert (1984) predicted that in vitro culture will have great potential for gene conservation.

Protoplast Culture

This is a method in which cell walls are removed from the plant cells to "produce isolated protoplasts" (Evans & Cocking 1977). This method allows for somatic hybridization, in which two different protoplasts from different parents fuse combining genomes of the parents. This technique has great value for tree breeders. It can overcome genetic barriers in the crossing process. For example, an attempt to hybridize ponderosa pine (Cal.) with *P. tenuifolia*, *P. pringlei*, and *P. lawsonii* has remained unsuccessful (Conkle and Critchfield 1988). By applying protoplast culture, these crosses would become possible. Another advantage of somatic hybrids is that they can completely inherit genomes from both parents. In routine sexual production, progeny or hybrids usually do not completely inherit the genome from father. This is because during the process of fertilization, "hereditary characteristics localized in the cytoplasm are usually only inherited from the mother." (Pierik 1987e).

CONCLUSION

In vitro culture techniques are becoming powerful tools in mass propagation and tree improvement programs of gymnosperm species. Among gymnosperm species, in vitro culture of ponderosa pine has made considerable progress in a relatively short period of time. However, it is still in an experimental stage. With a future effort in fundamental growth process research and development of in vitro culture procedure for ponderosa pine, in vitro culture technology can make a great contribution to tree improvement programs for ponderosa pine. This technology can assist by reducing breeding cycles, providing for rapid genetic bioassays, gene conservation, and somatic hybridization to create unique genotype for future forests.

LITERATURE CITED

- Aboel-Nil, N.M. 1987. Tissue culture of Douglas fir and western North American conifers. p. 80-100. *In* Cell and Tissue Culture in Forestry. Vol.3. Maritinus Nijhoff Pub., Boston. 416 pp.
- Aitken-Christie, A.P. Singh, and H. Davies. 1988. Multiplication of meristematic tissue: a new tissue culture system for radiata pine. p. 413-431. *In* Genetic Manipulation of Woody Plants. Plenus Press, New York. 519 pp.
- Amerson, H.V., L.J. Frampton, Jr., R.L. Mott, and P.C. Spaine. 1988. Tissue culture of conifers using loblolly as a model. p. 117-137. *In* Genetic Manipulation of Woody Plants. Plenum Press, New York. 519 pp.
- Arnold, S.V. and I. Hakman 1988. Plantlet regeneration *in vitro* via adventitious buds and somatic embryos in Norway spruce (*Picea abies*). p. 199-215. *In* Genetic Manipulation of Woody Plants. Plenum Press, New York. 519 pp.
- Attree, S;M., F. Bekkaoui, D.I. Dunstan, and L.C. Fowke. 1987. Regeneration of somatic embryos from protoplasts isolated from an embryogenic suspension culture of white spruce (*Picea glauca*). Plant Cell Reports 6:480-483.
- Ball, E.A. 1987. Tissue culture multiplication of *Sequoia* p. 146-158. *In* Cell and Tissue Culture in Forestry. Vol.3. Maritinus Nijhoff Pub., Boston, 416 pp.
- Bilderback, D.E. and D.E. Ellis. 1985. Effects of varying the nutrient constituents on bud production by cultured embryos of *Pinus ponderosa*. American Journal of Botany Abstracts 72(6):906.
- Bonga, J.M. 1987. Clonal propagation of mature trees: problems and possible solutions. p. 249-271. *In* Cell and Tissue Culture in Forestry. Vol.1. Maritinus Nijhoff Pub., Boston. 422 pp.
- Boulay, M. 1987. Conifer micropropagation: applied research and commercial aspects. p. 185-206. *In* Cell and Tissue Culture in Forestry. Vol 3. Maritinus Nijhoff Pub., Boston. 416 pp.
- Boulay, M.P., P.K. Gupta, P. Krogstrup, and D.J. Durzan. 1988. Development of somatic embryos from cell suspension cultures of Norway spruce (*Picea abies* Karst.) Plant Cell Reports 7:134-137.
- Cheng, T.Y. 1975. Adventitious bud formation in culture of Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco). Plant Science Letter. 5:97-102.
- Conkle, M.T. and W.b. Critchfield. 1988. Genetic variation and hybridization of ponderosa pine. p. 27-43. *In* Symposium Proceedings, Sept. 29 - Oct. 1, 1987. Spokane, Washington.
- Diner, A.M. and R.L. Mott. 1982. Axenic cultures from basidiospores of *Cronartium ribicola*. Canadian Journal of Botany 60:1950-1955.
- Durzan, D.J. and P.K. Gupta. 1987. Somatic embryogenesis and polyembryogenesis in Douglas-fir cell suspension cultures. Plant Science 52:229-235.
- Ellis, D.E. and D.E. Bilderback. 1983. The use of sterile tissue culture to induce multiple buds on *Pinus ponderosa*. American Journal of Botany Abstracts. 70(5):85.
- Ellis, D.E. and D.E. Bilderback. 1989. Temporal competence of embryonic *Pinus ponderosa* cotyledons to form multiple buds *in vitro*. American Journal of Botany. 76(3):348-355.
- Evans, P.K. and E.C. Cocking. 1977. Isolated plant protoplasts p. 103-135. *In* Plant Tissue and Cell Culture. University of California Press, Berkeley. 614 pp.
- Gresshoff, P.M. and C.H. Doy. 1972. Development and differentiation of haploid *Lycopersicon esculentum* (tomato). Planta. 107:161-170.
- Gresshoff, P.M. 1978. Phytohormones and growth and differentiation of cells and tissues cultured *in vitro*. p. 1-29. *In* Phytohormones and Related Compounds: a Comprehensive Treatise. Elsevier/North-Holland Biomedical Press. Amsterdam. 648 pp.
- Gupta, P.K. and D.J. Durzan. 1987. Somatic embryos from protoplasts of loblolly pine proembryonal cells. Biotechnology 5:710-712.
- Haberlandt, G. 1902. Sitzungsber Akad. Wiss. Wien. Math. Nat. Classe III, Abt. 1:69-92; translation in Botanic Review 35: 59-88.
- Haissig, B.E., N.D. Nelson, and G.H. Kidd. 1987. Trends in the use of tissue culture in forest improvement Biotechnology 5:52-59.
- Hakman I. and L.C. Fowke. 1987. An embryogenic cell suspension culture of *Picea glauca* (White spruce). Plant Cell Reports 6:20-22.
- Hakman I. and S.V. Arnold. 1988. Somatic embryogenesis and plant regeneration from suspension cultures of *Picea glauca* (White spruce). Physiologia Plantarum 72:579-587.
- Hakman, I., L.C. Fowke, D.V. Arnold and T. Eriksson. 1985. The development of somatic embryos in tissue cultures initiated from immature embryos of *Picea abies* (Norway spruce). Plant Science 38:53-59.
- Harvey, A.E. and J.L. Grasham. 1969. Procedures and media for obtaining tissue cultures of 12 conifer species. Canadian Journal of Botany 47:547-549.
- Horgan, K. 1987. *Pinus radiata*. p. 128-14. *In* Cell and Tissue Culture in Forestry. Vol.3. Maritinus Nijhoff Pub., Boston. 416 pp.
- Kartha, K.K., L.C. Fowke, N.L. Leung, K.L. Caswell, and I. Hakman. 1988. Induction of somatic embryos and plantlets from cryopreserved cell cultures of White spruce *Picea glauca*. Journal of Plant Physiology 132:592-539.
- Krogstrup, P., E.N. Eriksen, J.D. Moller, and H. Rouland. 1988. Somatic embryogenesis in Sitka spruce (*Picea sitchensis* (Bong.) Carr.). Plant Cell Reports 7:594-597.
- Lesney, M.S., J.D. Johnson, T. Karhnak, and M.W. McCaffery. 1988. *In Vitro* manipulation of slash pine (*Pinus elliotii*). p. 43-55. *In*

- Genetic Manipulation of Woody Plants. Plenum Press, New York. 519 pp.
- Linsmaier, E.M. and F. Skoog. 1965. Organic growth factor requirements of tobacco tissue cultures. *Physiologia Plantarum*, 18:100-127.
- Mehra-Palta, A. and D.G. Thompson. 1987. Tissue culture of eastern North American conifers. p. 61-79. *In* Cell and Tissue Culture in Forestry, Vol. 3. Martinus Nijhoff Pub., Boston. 416 pp.
- Minocha, S.C. 1980. Callus and adventitious shoot formation in excised embryos of white pine (*Pinus strobus*). *Canadian Journal of Botany*. 58:366-370.
- Minocha, S.C. 1987. Plant growth regulators and morphogenesis in cell and tissue culture of forest trees. p. 50-66. *In* Cell and Tissue Culture in Forestry. Vol.1. Martinus Nijhoff Pub., Boston. 422. pp.
- Mott and Amerson. 1984. Cultured cells of white pine show genetic resistance to axenic blister rust hyphae. *Science* 224:407-408.
- Murashige, T. and F. Skoog. 1962. A revised medium for rapid growth and bio-assays with tobacco tissue culture. *Physiologia Plantarum*. 15:437-469.
- Pierik, R.L.M. 1987a. Introduction. p. 3-20. *In* *In vitro* Culture of Higher Plants. Martinus Nijhoff Pub., Boston. 344. pp.
- Pierik, R.L.M. 1987b. Preparation and composition of nutrient media. P. 45-82. *In* *In Vitro* Culture of Higher Plants. Martinus Nijhoff Pub., Boston. 344 pp.
- Pierik, R.L.M. 1987c. Embryo culture. p. 139-148. *In* *In vitro* Culture of Higher Plants. Martinus Nijhoff Pub., Boston. 344 pp.
- Pierik, R.L.M. 1987d. Vegetative propagation. p. 183-230. *In* *In vitro* Culture of Higher Plants. Martinus Nijhoff Pub., Boston. 344 pp.
- Pierik, R.L.M. 1987e. Genetic manipulation. p. 259-279. *In* *In vitro* Culture of Higher Plants. Martinus Nijhoff Pub., Boston. 344 pp.
- Quoirin, M. and P. Lepoivre. 1977. Etudes de milieux adaptes aux cultures *in vitro* de *prunus*. *Acta Horticulturae*. 78:437-442.
- Schenk, R.U. and A. Hildebrandt. 1972. Medium and techniques for induction and growth of monocotyledonous and dicotyledonous plant cells culture. *Canadian Journal of Botany*, 50:199-204.
- Skoog, F. 1971. Aspects of growth factor interactions in morphogenesis of tobacco tissue cultures. p. 115-135. *In* Les Cultures de Tissue de Plantes. Colloques Internationaux Centre National de la Recherche Scientifique N. 193. Paris. 511 pp.
- Slack, S.A. 1988. Applications of tissue culture and micropropagation techniques to potato production. *American Potato Journal* 65:163-165.
- Street, H.E. 1977. Cell (suspension) culture-techniques. *In* Plant Tissue and Cell Culture. University of California Press, Berkeley. 614 pp.
- Teasdale, R.D. 1987. Micronutrients. p. 17-49. *In* Cell and Tissue Culture in Forestry. Vol.1. Martinus Nijhoff Pub., Boston. 422 pp.
- Thorpe, T.A. 1988. Physiology of bud induction in conifers *in vitro*. p. 167-184. *In* Genetic Manipulation of Woody Plants. Plenum Press, New York. 519 pp.
- Van Hooser, D.D. and D.E. Keegan. 1988. Distribution and volumes of ponderosa pine forests, p. 2-9. *In* Ponderosa Pine, the Species and its Management. Symposium Proceedings Sept. 29 - Oct. 1, 1987. Spokane, Washington 281 pp.
- Wolter, K.E. and F. Skoog. 1966. Nutritional requirements of *Fraxinus* callus cultures. *American Journal of Botany*, 53:263-269.
- Zobel, B. and J. Talbert. 1984. The genetic base and gene conservation. p. 467-476. *In* Applied Forest Tree Improvement. John Wiley & Sons Pub., New York. 622 pp.

Forest Diseases, Environmental Pollutants, and Other Stresses: Moderator's Comments

**Ralph Johnson
USDA Forest Service**

In this session, there were five presentations describing how to model diseases, pollutants, and stresses. There was one presentation on site index evaluation and one presentation giving an overview on diseases that alter the growth and yield of ponderosa pine.

Jeffrey Miller described a methodology where relative impacts of air pollutants on different species can be put into a model. This model can then be evaluated over differing time horizons and relative impacts noted. This technique has been used in the San Bernardino Mountains to evaluate ozone. Some parts of the system are still under development. Use of this technique allows for evaluation of pollution impacts when time constraints permit in-depth model development.

The second presentation, by Marcel Rejmanek, described methods for estimation of woody weed competition on a ponderosa pine plantation. Field measurement techniques were described. Permanent plots were established and plot maps created. Competition impact on conifer growth, as was reported in this presentation, is important where multi-resource objectives call for the retention of non-conifer vegetation on a site.

The last modeling presentation was by Terry Droessler. Use of an empirical growth model to reflect tree growth changes can present some questionable conclusions. In this presentation, a case is made for assuring the basic growth model function to mathematically portray the desired impact.

William Stansfield presented a brief synopsis of site quality measures. In multi-resource management, disciplines other than timber management may reference site productive capacity differently. This presentation describes the different methods (site index, soil/site relationships, and habitat type) and shows how these methods relate to currently recommended site index techniques.

The last presentation of the morning session was a review presented by Borys Tkacz of diseases impacting ponderosa pine. Dwarf mistletoe and root diseases were discussed in detail. Trends toward management prescriptions which emphasize multistory, unevenaged, and multispecies forests can increase these forest pests. This presentation generated numerous questions from the workshop participants.

AIRSILVA: A Model of Mixed Conifer Forest Response to Multiple Stress¹

Jeffrey Miller² and Lew Ladd³

Abstract. AIRSILVA is a model of mixed conifer forest community dynamics incorporating the population modeling capability of gap models and the mechanistic ecophysiology of process models to create a model where processes occur within individuals, and the failure of individuals to successfully complete processes results in population level dynamics.

The purpose of AIRSILVA is to synthesize the best available knowledge on the effects of air pollutants on the mixed conifer forests of southern California, and to project potential ecosystem responses under alternative pollution scenarios.

INTRODUCTION

Trees are notable for their long life-spans and large areas over which species or community types can be distributed. The scale of these organisms makes computer simulation modelling an important method for gaining insights into long-term community level responses of forests to multiple stresses. The stresses individual trees must deal with can be both natural, such as water or nutrient stress or man-caused such as ozone and acid-rain. But with the projected impacts of elevated CO₂, such as increased

temperatures and corresponding water stress, these will be hard to separate.

Ecosystem functioning can be described at many levels of resolution. At each level of resolution there are certain appropriate phenomena of interest depending on the rates of the processes involved (O'Neill et al., 1986). Four time scales based on the cycles of nature are the diurnal (within a day), the seasonal (within a year), successional (within the disturbance frequency but without genetic change), and evolutionary (with genetic change). At the successional level the responses of forests to stresses usually focuses on species composition through time. Population models, such as gap models (Shugart, 1984) or vital attribute models (Noble and Slatyer, 1980) have been used to project the impacts of various stresses on the course of succession for many ecosystems around the world. Another view of succession concentrates on the changes in the rates and magnitudes of the processes which control the functioning of the ecosystem. Understanding these processes does not depend on knowing which individual within a species or within functionally similar species actually performs the functions.

AIRSILVA is a combination of the population modeling capability of gap models, and the

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²Jeffrey Miller is a consultant to the Western Conifers Research Cooperative, US EPA Environmental Research Laboratory, Corvallis, Oregon.

³Lew Ladd is a senior programmer for NSI, US EPA Environmental Research Laboratory, Corvallis, Oregon.

Carbon and Nitrogen Flow in AIRSILVA.

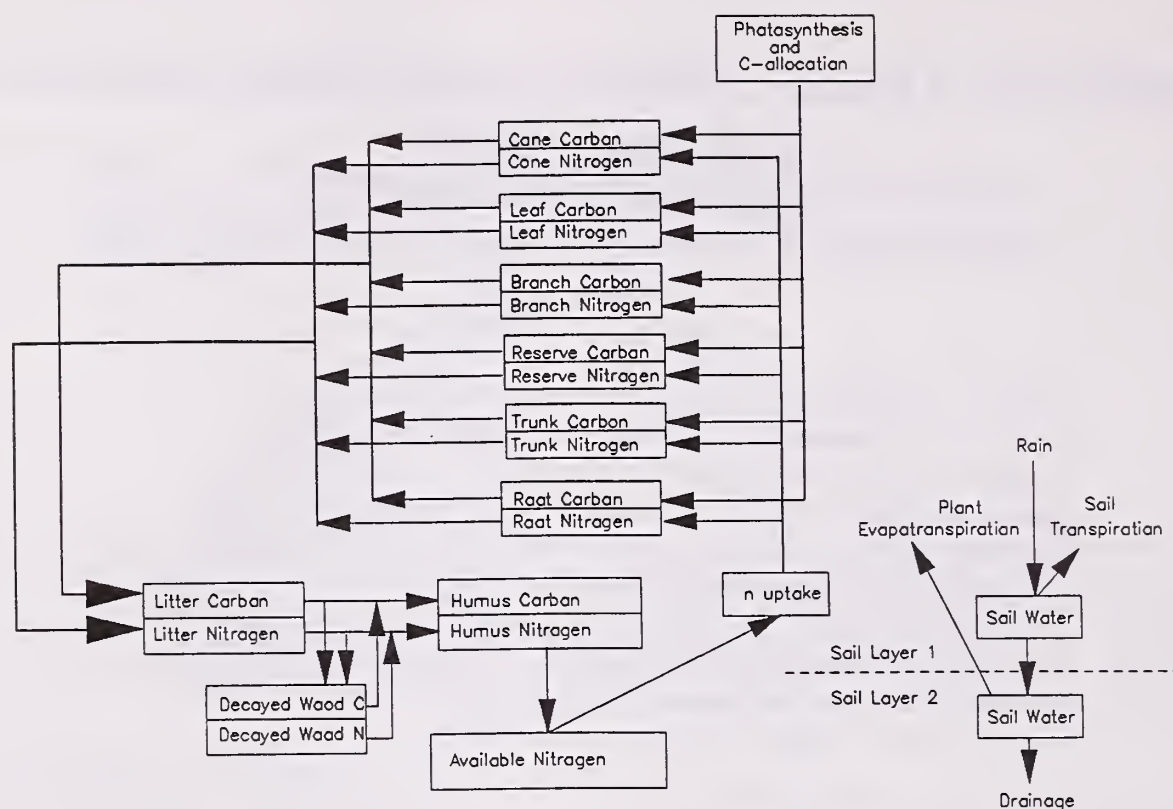


Figure 1. Each tree in AIRSILVA has 5 carbon compartments; leaves of up to 5 age classes, branches, trunk, roots, and cones. There are 4 corresponding nitrogen compartments; leaves of up to 5 age classes, wood (incorporating both branches and the trunk), roots and cones. Carbon acquisition of each tree is a function of environmental conditions and the leaf area. Carbon allocation is based on the trees desire to maintain an optimal carbon gain to nitrogen uptake ratio. Nitrogen uptake depends on the availability of nitrogen and the rooting volume. Nitrogen allocation at the community level is based on the relative demands of each individual tree and the decomposers. Nitrogen allocation within each tree depends on the relative sink strengths of each plant part. As litter ages it releases carbon and immobilizes nitrogen until it reaches a critical C/N ratio when it becomes humus and starts to release nitrogen as it continues to decompose.

mechanistic explanatory capability of process models. AIRSILVA is based on the gap model SILVA (Kercher and Axelrod, 1984a; 1984b) which is a version of the JABOWA model (Botkin et al., 1972) modified to simulate the mixed conifer forests of California and the roles of fire and SO_2 have on community composition. The modifications to SILVA replace the logistic growth function and rule-based growth constraining relationships found in most gap models with a simplistic set of ecophysiological functions that allow the effects of air pollutants to be incorporated with a degree of mechanistic realism.

The reason for emphasizing the mechanisms of plant growth is that air pollutant stress is not an external phenomena but is part of the system and causes the plant to emphasize different growth strategies. By modifying the patterns of allocation, as in increasing leaf area when the photosynthetic efficiency decreases, a plant may be able to compensate and forest succession over long time periods, thus retaining the capabilities of a gap model, and also explain the observed patterns as the result of the underlying controlling processes. AIRSILVA is envisaged to be the longest time-scale model of a set

of three hierarchical models. The other two models concentrate on the diurnal physiological responses of a forest canopy to pollutants, and the seasonal ecophysiological response of a whole tress. The purpose of these models is to synthesize the available understanding concerning the effects of air pollutants, specifically ozone and acid-rain, on ponderosa pine and the mixed conifer forests of the southern Sierra Nevada and San Bernardino Mountains as a contribution of the Western Conifers Research Cooperative to the National Acid Precipitation Assessment Program.

ASSUMPTIONS OF THE MODEL

AIRSILVA follows other gap models and simulates the growth of individual trees on a plot (Shugart, 1984). The size of the plot is determined by the requirements of a single individual of the species requiring the largest amount of space. When this large individual dies it creates a gap in the forest canopy. This opening is usually invaded by many individuals of a fast growing light-requiring species. As these individuals grow they shade one another and eliminate the shorter individuals. A second growth pattern consists of species which may be slower growing, but are tolerant of shade. The shade tolerant species can grow under a closed canopy of the light requiring species, and once the light requiring species die come to dominate the stand. This successional cycle can then repeat once the shade tolerant species dies, creating another gap.

Gap models have the ability to mimic the hypothesized pattern of forest succession, but do not explain succession as a function of underlying processes. Birth and death are simulated as random events which can be biased with rules relating to the environmental conditions. Each run of a gap model is a single possible sequence of random events, and the models are usually run many times to develop a central response tendency of a forest.

In AIRSILVA the rules found in other gap models that directly link the environment to growth have been replaced with rules relating the environment to physiological functions. This allows population level responses to be explained as a result of the underlying physiological processes. This also allows the plant to have the ability to compensate for the environment. The effects of air pollutants may be so subtle that they only show up in the plants compensatory processes rather than its overall response.

Unlike other gap models where a continuous supply of seeds of all species is assumed, the soil seed banks in AIRSILVA depend upon the reproductive efforts of the individuals on the plot. This follows the logic of the vital attributes model which emphasizes the idea that species composition after a disturbance depends upon the species ability to survive the disturbance as either a resistance adult or as a seed.

Each individual tree is described by a set of carbon and nitrogen contents in various plant parts (Figure 1). Within the plot there is no explicit spatial arrangement of the individual trees. The leaf area of each tree is distributed vertically into layers, and is assumed that the leaves in each layer are spread over the whole plot. The roots of each individual occupy a fraction of the total soil volume. It is assumed that these roots are evenly mixed throughout the complete soil volume. This effectively means that within a plot the trees are growing under or above each other, but not beside one another.

The model increments tree growth once a year based on photosynthate accumulated on monthly time steps. The monthly time step is used to incorporate both the fluctuations in total annual rainfall and the seasonal pattern of rainfall which determines the length of the summer drought. Monthly carbon acquisition is calculated with an instantaneous gas exchange model driven by the average environmental conditions during the month. Acquired carbon and nitrogen are placed into reserve compartments, and the annual allocation pattern is a function of the reserve nitrogen to carbon ratio. A lack of nitrogen will increase allocation to roots and a lack of carbon will increase allocation to leaves. Plant parts are assumed to maintain constant C/N ratios, so the total growth of all of the plant parts depends on the smaller of the two reserve pools.

Ozone is incorporated in the model as it is assumed to effect photosynthetic efficiency (Tingey and Taylor, 1982). Although acid rain has not been isolated as a major impact on western forests, AIRSILVA includes its possible effects on site nutritional balance first as a supply of nitrogen and then as a detrimental soil acidifier as deposition rates increase.

AIRSILVA is written in C for portability between personal computers, work stations, and main frames. In C the FORTRAN or BASIC subroutines are called functions. One of the strengths of object oriented computer languages such as C is the ability to organize related information into data structures which are addressable with a single variable name. AIRSILVA has two main data structures, the "tree"

Table 1. Information on each tree on the site is organized into a data structure called "tree". Of the thirty variable describing each tree the 12 parameters describe various properties of the tree, the 13 state variables describe the masses of carbon and nitrogen that comprise the tree and the accumulated ozone dose of each age class of leaves, and the 5 rate variables describe the transfer rates of carbon and nitrogen. Other information concerning each tree which does not need to be transferred between functions, such as the transpiration rate which is only used in the hydrology function, is not part of the "tree" structure.

Parameters:	tree number species code age annual growth ring width basal diameter height maximum branch mass attained crown thickness maximum crown thickness attained leaf area above canopy midpoint soil volume for water uptake soil volume for nitrogen uptake
State variables:	leaf mass (of up to 5 age classes) accumulated ozone dose (by leaf age class) carbon reserve mass branch mass trunk mass root mass new root mass cone mass leaf nitrogen content (by leaf age class) reserve nitrogen content wood (branch and trunk) nitrogen content root nitrogen content cone nitrogen content
Rate variables:	monthly average leaf conductance annual nitrogen uptake monthly net photosynthate (by leaf age class) annual wood respiration rate annual root respiration rate

and the "litter". Information on both the carbon and nitrogen masses of the parts of a tree, the exchange rates of these plant parts, as well as some general characteristics of the tree such as its height are arraigned in a linked list of objects called "tree". Similarly, each years litter production is separated by material type and placed in a linked list containing information on its carbon and nitrogen mass, age, material type, etc. By using a linked list structure instead of an array, information does not have to be moved around in the computers memory; only a pointer to the location of the information needs to be

updated. This data structure has greatly enhanced the computational speed of AIRSILVA and allowed model development to proceed on personal computers.

The data structure "tree" describing each tree consists of 30 variables (Table 1). Twelve parameters describe which tree the individual is (tree_number), its species, age, annual ring width, basal diameter, height, the volume of soil available for exploitation of water and nitrogen, and three values used to determine the base of the crown. Thirteen state

```

main()
{
  init_stand()
  for (year = 0 to number of years in run)
  {
    init_output()
    climate()
    birth()
    add_trees()
    community()
    get_leaf_area()
    for (month = 0 to 12)
    {
      hydrology()
      c_up()
    }
    decomp()
    newcohort()
    n_up()
    grow()
    carbon_alloc()
    fire_()
    kill()
    yearly_output()
  }
}

```

Figure 2. AIRSILVA consists of 13 primary functions and has a one year time-step except for the hydrology and c_up functions which have monthly time-steps. The initial stand conditions are defined in init_stand(). Within the yearly loop climate for the year is generated in climate(), new trees emerge in birth(), and community() defines some general conditions on the plot. The plot water balance is calculated once a month in hydrology(), and the effect this has on carbon uptake is calculated in c_up(). Once a year decomp() determines the breakdown of organic matter and nitrogen availability for uptake in n_up(). The function grow() determines the growth of each tree on the plot based on the acquired carbon and nitrogen. Fires may occur and kill individuals in the fire_() functions, and then kill() removes trees that have died either due to an inadequate carbon gain for the year or as the result of fire. Finally the yearly_output() summarizes values on the water balance of the plot, the carbon and nitrogen cycling, and the population dynamics of each of the species on the plot.

variables describe the carbon and nitrogen biomass compartments; leaf carbon and nitrogen (of up to five age classes), reserve carbon and nitrogen, branch carbon, trunk carbon, wood (both branch and trunk) nitrogen, root carbon and nitrogen, cone carbon and nitrogen, the new root carbon mass, and the accumulated ozone dose. Five rate variables; the leaf conductance, the net photosynthesis rate, the nitrogen uptake rate, and the wood and root respiration rates are also part of the tree structure since they are used

in several functions and need to be related to a particular tree. All of the masses maintained in the model are in kilograms, and the distances are in meters.

The model is built in modules (C functions) that exchange information. Each function can be modified and improved or treated as a black box as needs vary, as long as the function performs the minimal tasks required of it by other parts of the model. Because

the model includes numerous stochastic components it can be run several times and average responses determined, or the results of a single run can be analyzed.

AIRSILVA consists of 13 primary functions; `init_stand`, `init_output`, `climate`, `birth`, `community`, `hydrology`, `c_up`, `decomp`, `n_up`, `grow`, `fire_`, `kill`, and `yearly_output` (Figure 2). The function `init_stand` is called once at the beginning of each run to initialize the stand, and the other functions are then called once each year except for `hydrology`, and `c_up` which are called once a month.

Stand initialization

The `init_stand` function defines the initial conditions of the stand at the beginning of each run. The model starts with "post fire" conditions; there are no trees, and no above ground accumulated litter. There is root litter, soil organic matter (humus), and corresponding nitrogen contents, and an initial seed bank of each of the species. The `init_stand` function also calculates the total water storage capacity of the plot, which depends on the water holding capacity of the soil (l/m^3), the plot size and soil depth, and the rock content of the soil. The model starts with saturated soil water conditions.

The variables that summarize the conditions on the plot at the end of each year are initialized in the `init_output` function. The output variables summarize four general areas; plot water balance, nitrogen cycling, carbon cycling, and population dynamics.

Climate

The `climate` function corrects the monthly mean temperatures at the nearest weather station for the adiabatic lapse rate due to the elevation difference between the weather station and the plot being simulated. The number of degree-days over 5°C are summed, and the monthly potential total solar radiation is corrected for losses from clouds. The monthly mean and standard deviations for precipitation, ozone concentration, H^+ , N , and S deposition are supplied to the model as required data. For each month of the year the `climate` function generates values for these parameters from normal distributions.

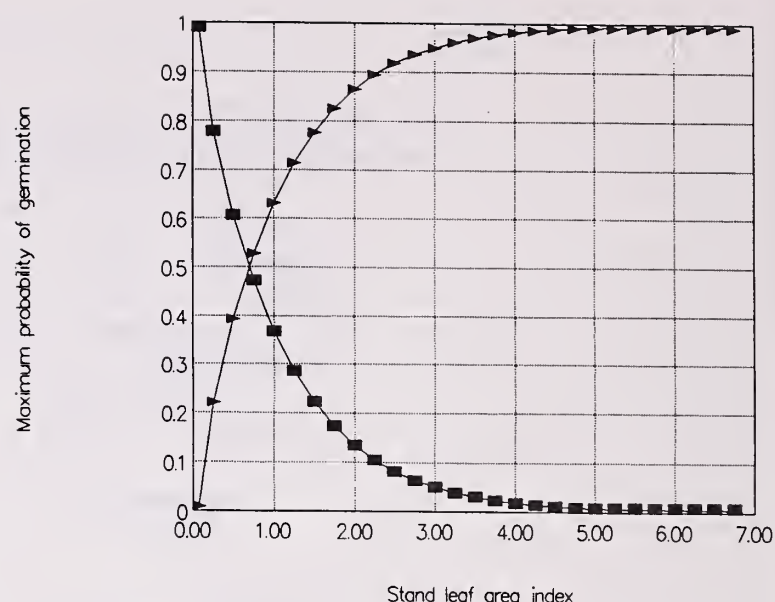


Figure 3. If the accumulated degree days at a site are within the species specific minimum and maximum tolerable then germination success depends on the species sensitivity to shade. Species are either shade requiring (▲) or shade intolerant (■). The annual germination rate (seedlings/ m^2) is a uniform random number up to the potential maximum described by the light response function.

Birth

The `birth` and the `add_trees` function that `birth` calls add new individuals to the stand. If the annual degree day total is between the species specific minimum and maximum required for germination a fraction of the seeds in the soil germinate. The number of seeds that germinate is determined stochastically, with shade requiring and shade intolerant species having two different probability patterns as a function of the stand leaf area index (Figure 3). With increasing leaf area the shade intolerant trees have a decreasing probability of germination, and the shade requiring trees have an increasing probability of germination.

New seeds are added to the soil seed bank based on the reproductive efforts of the trees on the plot, and from off of the plot. This latter source prevents local extinctions of a species (as represented by either an adult or a seed) on the plot. Once the `birth` function has calculated the number of new individuals of each species to be added to the plot, the initial masses of the seedlings and the other parameters maintained for each individual are defined in function `add_trees`. Seeds lose viability and die following values reported for the model SILVA (Kercher and Axelrod, 1981).

Community totals

The community function sorts the linked list of trees by height so the leaf area index above each individual can be calculated in the function `get_leaf_area`. The leaf canopy of the community is divided into 25 layers from the top of the tallest tree to the ground. The leaf area in each layer is assumed to cover the whole plot. The leaf area of each individual is distributed vertically along its trunk from the crown base to the top of the tree following a normal distribution. The leaf area each individual contributes to the community canopy profile is summed. The leaf area above an individual consists of the leaf area in the canopy layers above the midpoint of the individuals canopy, and half of the leaf area of the layer at the midpoint. The light level at the midpoint of each individuals canopy is calculated following Beer's law (exponential decline). It is assumed that the leaves of each age class are equally distributed vertically, so all leaf classes experience the same light levels.

The community function also determines the volume of soil that the roots of each tree can potentially exploit for water and nitrogen. The potential maximum volume of soil that the roots of the community can exploit for water is the sum of the volumes of each individual. These cylindrical volumes are calculated from the root mass of the individual converted to a length, and a radius around the root. Water uptake is assumed to occur along the complete root length. When the potential exploitable volume of the community exceeds the actual soil volume, each individual then exploits a fraction of the total soil volume equal to its volume divided by the community volume. Nitrogen uptake follows a two dimensional version of the same algorithm since it is assumed that the nitrogen dynamics take place at the surface of the soil. The nitrogen exploitable area is the rectangular area described by the root length and the exploitable distance from the root. As with the distribution of leaf area there is no spatial component in the distribution of each individuals roots in the community. All of the roots can explore the complete soil volume of the plot. The roots are also not distributed vertically, but it may be more appropriate to distinguish two rooting zones, and have the trees either allocate to growth of surface roots for nitrogen uptake, or deeper roots for water uptake.

When the soil volume that could be exploited by the whole community is less than the total soil volume, the rate of nitrogen and water return to an individual limited by the carbon investment into roots. When the soil volume that could be exploited by the

whole community is greater than the actual soil volume, the rate of return to an individual depends on its investment relative to all the other individuals. Since less than optimal C/N ratios within a tree will cause more investment into roots, this process of return related to investment simulates the individuals competing for nitrogen and water.

Plot hydrology

The plot water balance is calculated in the hydrology function and the `satvap` and `penmon` functions which hydrology calls. During the one year time step of AIRSILVA the hydrology function is called once a month in order to capture both the variations in total annual rainfall, and the seasonal pattern of rainfall as it influences the summer drought.

On a monthly time step the random amount of rainfall generated in the climate function is added to the top soil layer. If this new soil water content is greater than the water holding capacity of the layer then the excess is transferred to the second soil layer. If the second soil layer then contains more water than its holding capacity the excess is lost to drainage. The soil water contents of the two soil layers determine the soil water potentials of the two layers following a generalized soil water content to soil water potential function (Jeffrey, 1987). The water potential of the upper layer determines the soil surface conductance (Figure 4) which is then used in the Penman-Monteith equation (Monteith, 1973) to calculate actual soil evaporation.

It is assumed that the plants only extract water from the lower soil layer. The potential maximum water uptake is determined by the volume of soil exploited by the roots and the soil water content. The monthly average leaf conductances to water loss are based on the soil water potential, the monthly average light level, and the vapor pressure deficits following Jarvis (1976) as modified by Landsberg (1986). Actual transpiration is then calculated by the Penman-Monteith equation, but can not exceed the potential maximum uptake. After soil evaporation has removed water from the upper soil layer, and the trees have removed water from the lower soil layer, there is vertical water movement based on a soil hydraulic conductivity value determined from the average of the water potentials of the two soil layers.

The soil is assumed to have a capacity to buffer H^+ deposition. If the accumulated deposition occurs faster than the soils ability to regenerate this buffering capacity the system will cross a threshold and nitrogen

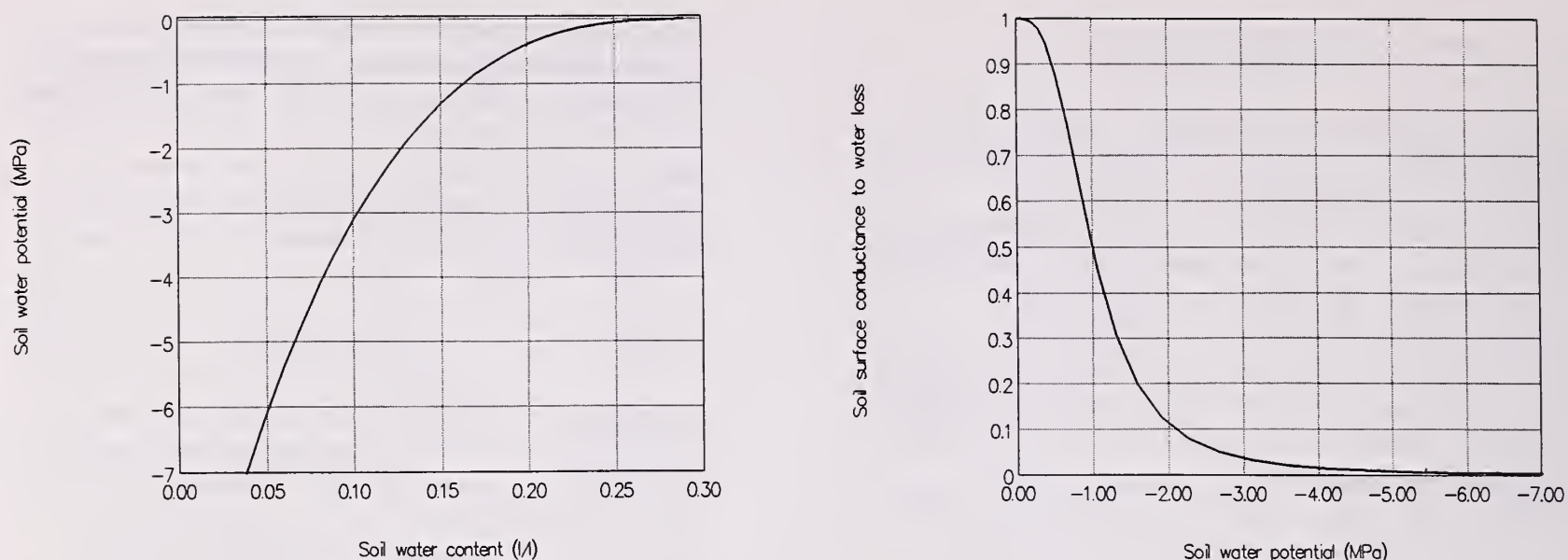


Figure 4. Soil water potential is calculated from a general relationship between soil water potential and soil water content (Jeffrey, 1987). The soil surface conductance to water loss is calculated from soil water potential based on a general function from Landsberg (1986). Both functions can be easily parameterized to fit soils of a specific site.

will begin to be leached from the soil. The rate of leaching is proportion to the available nitrogen and how far the soil buffering capacity has been pushed beyond the threshold.

Carbon acquisition

Along with the hydrology function carbon acquisition and respiration costs are calculated in function `c_up` once a month within the basic yearly time-step of the model. The average rate of photosynthesis for the month is calculated following Landsberg (1986) from the average leaf conductance determined in the hydrology function, temperature, photosynthetically active radiation, external CO_2 concentration, and the species specific potential maximum rate. This instantaneous rate is then multiplied by the day length and the number of days in the month. The photosynthesis equation incorporates leaf respiration, and the resulting net photosynthesis is calculated for each of the leaf age classes present on the tree. Leaf, wood, and root respiration rates depend on a base rate and a Q_{10} temperature function.

As leaves age the maximum photosynthetic rate decreases (Coyne and Bingham, 1982). Based on the field measurements of Coyne and Bingham (1981) the maximum rate of photosynthesis is assumed to decrease linearly with accumulated ozone dose. The

ozone dose depends on the external concentrations and the leaf conductance. The maximum rate of photosynthesis also decreases linearly when leaf nitrogen contents are less than an assumed optimum. The production of photosynthate is assumed to require nitrogen. The carbon gain of all of the trees increases the plant nitrogen demand used in the decomposition function to allocate nitrogen between the trees and the decomposition processes.

Decomposition

The decomp function follows the decomposition routine developed by Pastor and Post (1985) in the gap model LINKAGES. Litter generated in the function `grow` is of one of five materials; root, leaf, twig, small wood, or big wood. Each year a cohort of each class of material may be generated (as described in function `grow`). Each of these cohorts is then place in the linked list of cohorts and begins the decomposition process.

Each cohort of litter has a carbon and nitrogen content. Each year the material decomposes and releases carbon and immobilizes nitrogen until the material has reached a critical C/N ratio. These threshold C/N ratios vary depending on the type of material, and determine when the material is either transferred to the humus pool or the decayed wood pool in the case of the two classes of wood. Decayed

wood continues to release carbon and immobilize nitrogen, but at a faster rate than the two types of wood litter. The humus also releases carbon, but in doing so releases nitrogen for either uptake by the plants or the decomposition process.

Because the decomposition of each cohort of litter and each tree is competing for the available nitrogen a total demand is calculated based on how much nitrogen all of the trees need to satisfy their growth, and how much nitrogen each decomposing litter cohort could immobilize as it releases carbon. If this total demand is less than the available nitrogen then each cohort releases its complete amount of carbon, and immobilizes its complete amount of nitrogen. If the total demand is greater than the available nitrogen then the fraction of the available nitrogen each cohort can immobilize is proportional to its demand divided by the total demand. The amount of nitrogen immobilized then determines the amount of carbon released.

The potential rate of carbon release is presently a fixed fraction depending on litter material. The nitrogen that is immobilized in releasing this carbon depends on the litter material. Carbon release should be a function of evapotranspiration and litter lignin to nitrogen contents as in LINKAGES, if these regression equations can be developed for the litter in southern California. Following LINKAGES humus releases 3.5% of its carbon and nitrogen each year, and as with the litter decomposition this should be made a function of the soil moisture availability and humus quality. Atmospherically deposited nitrogen is assumed to join the available nitrogen pool, and there is a fixed soil weathering rate adding nitrogen to the soil.

Nitrogen uptake

Nitrogen uptake by each individual tree is calculated in the function `n_up`. The previous years growth in function `grow` defined a demand for nitrogen by all of the trees. This years carbon acquisition increased the total plant demand. The fraction of this total demand which can be satisfied was decided in the `decomp` function which divided the total available nitrogen between the trees as a group and the decomposition processes. Within function `n_up` each tree receives a fraction of the nitrogen available to the trees. The amount of nitrogen an individual can take up is based on either the absolute volume of soil exploited, or the relative volume of the individual as a fraction of the complete community as described earlier.

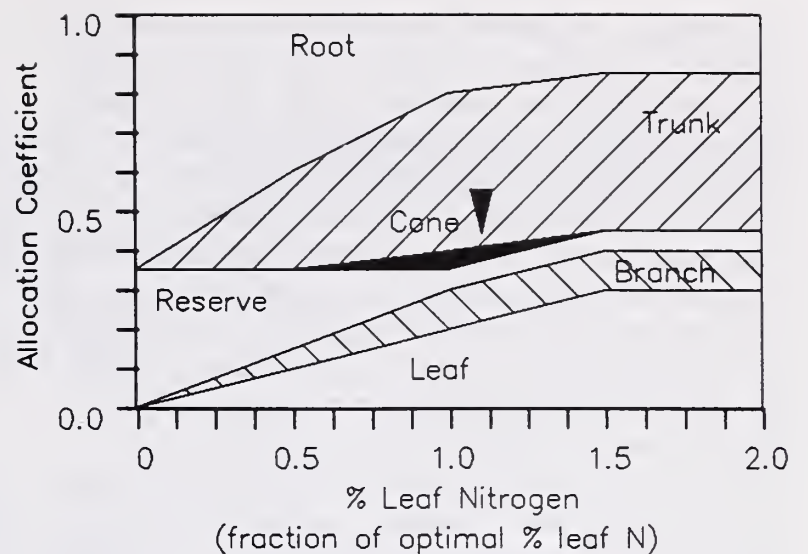


Figure 5. Allocation of carbon and nitrogen to the various plant parts depends on the ratio of reserve nitrogen to reserve carbon. The various plant parts have fixed nitrogen contents per unit carbon so the total amount of growth that can occur in a year is limited by the smaller of the two reserve supplies.

Growth and allocation

The function `grow` takes the nitrogen uptake values from the `n_up` function and the carbon acquisition and respiration values from the `c_up` function and calculates the net carbon available for growth. The function then calls the `carbon_alloc` function which determines the allocation patterns for both carbon and nitrogen, and increments the plant masses (i.e. growth). If any of the plant parts are to be shed the `grow` function also accumulates this years litter.

Each of the leaf age classes must be a net exporter of carbon otherwise the age class is declared dead. Premature leaf death occurs when photosynthesis has been inhibited by exposure to ozone. Re-translocation of nitrogen and carbon out of a leaf class dying prematurely is not as efficient as when leaves die naturally. Each species has a maximum leaf life span, and the leaf class exceeding this age is transferred to leaf litter. Some of the nitrogen and carbon is re-translocated to the reserve compartments. Re-translocation is not completely efficient and a fraction of the nitrogen in the leaves becomes leaf litter nitrogen and most of the leaf carbon becomes leaf litter. The one year time-step of the model make realistic fine root turn-over difficult

to simulate. In AIRSILVA half of the root mass is defined to turn-over each year. This allows the fine root mass to not be completely dependant on each years allocation to roots and allows the mass to increase as the tree grow. Root nitrogen is re-translocated from the roots and a fraction is transferred to root litter nitrogen. Some of the root carbon is also re-translocated to reserves, and the rest becomes root litter. Branch shedding occurs when there is more branch mass than is needed to support the leaf mass. Branch shedding removes nitrogen from the wood nitrogen pool in relation to the amount of branch mass shed. No carbon is assumed to be returned when branches are shed. After the wood and root respiration costs have been satisfied, the net photosynthate is added to the reserve compartment. If the carbon reserves of a tree become negative then the tree is dead.

The allocation pattern for assigning carbon and nitrogen to leaves, reserve, branches, trunk, reproduction, and roots is a function of the reserve nitrogen to reserve carbon ratio (Figure 5). If the plant is light limited then the carbon reserves will decrease in relation to the nitrogen reserves. With high N:C ratios allocation shifts from roots and branches to leaves and trunk. If the N:C ratio decreases due to nitrogen limitations then allocation is shifted from the leaves, branches, and trunk to the roots.

The various plant parts are assumed to have constant nitrogen to carbon ratios, which define how much nitrogen is required to balance the allocation of carbon. If the required nitrogen is less than the reserve nitrogen then allocation uses all of the reserve carbon and as much of the nitrogen as is needed. If there is not enough nitrogen to satisfy all of the carbon allocation then allocation proceeds to the limit of the nitrogen supply. The allocation of carbon and nitrogen from the reserves back to the reserves allows the plant to maintain a supply to live on when conditions are less favorable.

Growth respiration and the cost of converting photosynthate into plant parts accounts for a fraction of the material allocated to each plant part. The model does not presently account for secondary leaf thickening, or allow partial death of any leaf age class.

When the cone carbon pool reaches 10 kg there is a reproduction event and the pool is set to zero. This event translates to a potential maximum number of viable seeds, depending on the cone nitrogen content. Less than an optimum C/N ratios cause fewer viable seeds. The 10 kg threshold value needs

to be adjusted so that there is an appropriate periodicity in reproduction determined by the length of time it takes for the plant to accumulate sufficient reserves.

The basal diameter and height of the tree are calculated by turning the trunk mass into a cone shaped volume which has a species specific height to diameter ratio. The crown of the tree is initially distributed from the top of the tree to the ground. When the first branch shedding occurs a crown depth is defined as the height of the tree at that point. The branch mass is also recorded as the maximum branch mass. As the tree continues to grow the crown becomes a fraction of the total height of the tree equal to the crown depth. If the branch mass falls below the maximum branch mass the crown depth decreases. This allows AIRSILVA to simulate the observed pattern of ozone killing the lower branches and decreasing the crown ratio of ponderosa pine (Miller and McBride, 1988).

Fire

The set of fire_ functions calculate a probability of fire ignition, and then fire propagation based on the fuel load. Fires require sufficient litter load to ignite, and once burning kill trees based on their height and sensitivity to fire. The model views the linked list of trees organized by height as a fire ladder, and flames can jump up this ladder killing individuals until there is a step in height too large to jump. The size of the step that stops the fire ladder depends on moisture conditions, with drier conditions allowing the fire to jump larger steps. Sensitive species which have thin barks are killed whether or not their canopy is burned as in the model SILVA (kercher and Axelrod, 1981).

Death

The function kill removes individuals from the linked list of trees that have been tagged as DEAD in the function grow or the function fire_. When individuals die the leaf carbon and nitrogen contents are transferred to leaf litter as is the plant reserve carbon and nitrogen. The branches on the tree and the cones are transferred to the twig litter class and their nitrogen contents are transferred to the twig litter nitrogen pool. The trunks of the tree are either transferred to big wood or small wood litter depending on whether the trunk basal diameter was greater than 0.1m. Root carbon contents and nitrogen contents are transferred to root litter.

Table 2. AIRSILVA generates output files concerning the annual hydrological balance of the plot, the nitrogen cycling, the carbon cycling, the number of individuals by 0.1 m increments in basal diameter of each species, and a file following one specific tree.

AIRSILVA annual output values	
Water balance:	total rainfall soil drainage potential soil evaporation actual soil evaporation potential plant evapotranspiration actual plant evapotranspiration average soil water content (2 soil layers) average soil water potential (2 soil layers)
Nitrogen cycling:	potential nitrogen immobilization by decomposition actual nitrogen immobilization by decomposition potential plant uptake actual plant uptake mineralized total available leached leaf litter nitrogen content twig litter nitrogen content large woody debris nitrogen content small woody debris nitrogen content root litter nitrogen content decayed wood nitrogen content humus nitrogen content leaf nitrogen content by species reserve nitrogen content by species wood nitrogen content by species root nitrogen content by species cone nitrogen content by species
Carbon cycling:	leaf litter mass twig litter mass large woody debris mass small woody debris mass root litter mass decayed wood mass humus mass leaf mass by species reserve mass by species wood mass by species root mass by species cone mass by species
Population dynamics:	number of individuals by 0.1m increments in basal diameter by species number of viable seeds per m ² by species
Single tree:	leaf mass (of up to 5 age classes) reserve carbon content branch mass trunk mass root mass new root mass cone mass leaf nitrogen contents (by age class) reserve nitrogen content wood nitrogen content root nitrogen content cone nitrogen content annual growth ring width basal diameter height leaf area index above the canopy midpoint

Annual summaries

The yearly_output function generates output files on the nitrogen cycling, carbon cycling, plot hydrological balance, and the population dynamics of each species on the plot (Table 2). Individual trees can also be tracked in a fifth output file.

USES OF THE MODEL

AIRSILVA will be used to simulate three areas of ecosystem functioning; the hydrological balance, nitrogen cycling, and carbon cycling, and the effects these processes have on the species composition and size structure. The model will have the ability to investigate how these processes influence species succession, and how the shift in species composition influences the underlying ecosystem processes. AIRSILVA will be used to simulate the four broad areas; water balance, nitrogen cycling, carbon cycling, and population dynamics under natural conditions i.e. with "pre-man" fire frequency, with fire suppression, with the natural fire frequency and ozone, with the natural fire frequency and acid rain, and with actual conditions i.e. fire suppression, ozone, and acid rain. The ecosystem responses to various future patterns of air pollutant emissions will also be investigated as part of the National Acid Precipitation Assessment Program.

LITERATURE CITED

- Botkin, D.B., J.F. Janak, and J.R. Wallis, 1972. Some ecological consequences of a computer model of forest growth. *Journal of Ecology* 60: 849-872.
- Coyne, P.I., and G.E. Bingham, 1981. Comparative ozone dose response of gas exchange in a ponderosa pine stand exposed to long-term fumigations. *Journal of the Air Pollution Control Association* 31(1): 38-41.
- Coyne, P.I., and G.E. Bingham, 1982. Variation in photosynthesis and stomatal conductance in an ozone-stressed ponderosa pine stand: Light response. *Forest Sci.* 28(2): 257-273.
- Jarvis, P.G., 1976. The interpretations of the variations in leaf water potential and stomatal conductance found in canopies in the field. *Phil. Trans. R. Soc. Ser. B* 273: 593-610.
- Jeffrey, D.W., 1987. Soil-plant relationships: an ecological approach. Timber Press, Oregon. 295pp.
- Kercher, J.R., and M.C. Axelrod, 1981. SILVA: A model for forecasting the effects of SO₂ pollution on growth and succession in a western coniferous forest. UCRL-53109, Lawrence Livermore National Laboratory, California, USA. 72pp.
- Kercher, J.R., and M.C. Axelrod, 1984a. A process model of fire ecology and succession in a mixed-conifer forest. *Ecology* 65(6): 1725-1742.
- Kercher, J.R., and M.C. Axelrod, 1984b. Analysis of silva: a model for forecasting the effects of SO₂ pollution and fire on western coniferous forests. *Ecological Modelling* 23: 165-184.
- Landsberg, J.J., 1986. Physiological ecology of forest production. Academic Press, New York. 198 pp.
- Miller, P.R., and J.R. McBride, 1988. Trends of ozone damage to conifer forests in the western United States, particularly southern California. Presented at IUFRO Conf.: Air pollution and forest decline. Interlaken, Switzerland Oct 3-6, 1988.
- Monteith, J.L., 1973. Principles of environmental physics. Edward Arnold Ltd, London. 241 pp.
- Noble, I.R., and R.O. Slatyer, 1980. The use of vital attributes to predict successional changes in plant communities subject to recurrent disturbances. *Vegetatio* 43: 5-21.
- O'Neill, R.V., D.L. DeAngelis, J.B. Waide, and T.F.H. Allen, 1986. A hierarchical concept of ecosystems. Princeton University Press, New Jersey. 253 pp.
- Pastor, J., and W.M. Post, 1985. Development of a linked forest productivity-soil process model. ORNL/TM-9519. Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA. 162 pp.
- Shugart, H.H., 1984. A theory of forest dynamics. Springer-Verlag, New York. 278 pp.
- Tingey, D.T., and G.E. Taylor, Jr., 1982. Variation in plant response to ozone: A conceptual model of physiological events. In: Unsworth and Ormrod. Effects of gaseous air pollutants in agriculture and horticulture: 113-138.

Quantification and Prediction of Woody Weed Competition in Ponderosa Pine Plantations¹

Marcel Rejmanek and John J. Messina²

Abstract.-- Developing methods for quantifying competition is essential for forest vegetation management. Angular neighborhood competition index was calculated using field data on shrub species. Regression analysis revealed that the growth rate of ponderosa pine was negatively and significantly dependent on this index. Path analysis indicated only negligible contribution of competition for soil moisture to the total competition influence of shrubs. Irrigation experiments supported this conclusion.

INTRODUCTION

A common assumption in mediterranean and sub-mediterranean climates is that the success of reforestation is dependent upon soil water availability which is negatively influenced by the amount of competing vegetation. Previous forest management practices to reduce stresses imposed on conifer seedlings by woody weeds have emphasized the use of herbicides, but an increasing public interest concerning health and ecological aspects of extensive forest herbicide use has stimulated research into other, alternative solutions. Some very basic questions remain unresolved: How to quantify and predict stressful conditions for conifer seedlings? When are herbicide applications necessary and when are tree yield losses comparable with the price of herbicides and/or other investments? What are the best estimates of economic thresholds? Answering these questions would certainly help reduce herbicide use in revegetation programs. Development of biologically sound, practical, and efficient methods for the study of woody weed - crop tree competition seems to be the first logical step in this effort.

Implementation of large-scale chemical brush control is based on many competition studies showing the importance of mean woody weed density and/or cover on growth and survival of crop trees (e.g., Stewart et al. 1984, Radosovich 1984, White 1986, Petersen et al. 1988). These approaches assume that average density or cover provide effective predictors of the state of the tree population without considering individual variation (Firbank &

Watkinson 1987, Rejmánek et al. 1989). However, trees respond primarily to the proximity and behavior of neighboring plants and not to mean density or cover of woody weeds. By ignoring local interactions among individual plants, the real mechanisms of interference are obscured. Determining whether some or all of the neighbors are actual competitors, and what degree of stress each imposes on the focal plant, are unresolved problems.

This shortfall has warranted the development of spatially explicit and size-weighted expressions known as competition or neighborhood indices (Hegyi 1974, Lorimer 1983, Weiner 1984, Silander & Pacala 1985, Rejmanek & Messina 1989). We believe that a neighborhood approach, in which the attributes of neighbours (e.g., number, distance, spatial arrangement) are considered as they effect a focal plant, affords a number of advantages in examining woody weed - crop tree interference. Some of these competition indices represent promising candidates for competition functions in forest vegetation models, and their predictive value is being evaluated in both experimental and regular forest plantations using linear and nonlinear regression analysis. This analysis will be used later for estimation of economic thresholds. Because individual trees instead of means for individual experimental stands are used in the analyses, the neighborhood competition approach requires a much smaller total research area than methods mentioned earlier.

Our major goal is to evaluate indices of neighborhood interference in crop tree-woody weed situations with respect to (i) effective neighborhood radius, (ii) species differences, and (iii) soil moisture regime. Tree stem diameter, height, stomatal conductance, and net photosynthetic rate are used as indicators of stress and yield losses caused by woody weed competition. Results will be interpreted in terms of economic thresholds and management options (e.g., justification of the necessity and size of mulch collars around conifer seedlings in those areas where use of herbicides has been suspended by court action (Craig & McHenry 1988, Averill 1989, Smith 1989).

¹Paper presented at the conference on Multiresource Management of Ponderosa Pine Forests, Flagstaff, AZ, November 14-16, 1989.

²Marcel Rejmánek is Associate Professor of Botany and John J. Messina is Research Assistant, University of California, Davis, CA.

There have been very few silvicultural experiments in which water is the independent variable (Axelsson & Axelsson 1986, Brix 1972, Jarvis 1985, Kramer & Kozlowski 1979, Landsberg 1986, Newton et al 1986). These experiments ignored the role of weeds. In spite of the fact that competition for moisture between woody weeds and conifers is supposed to be the most important process determining success or failure of forest plantations in California and some other states (Radosevich 1984, Carter et al. 1984, Sands & Nabiar 1984, Shainsky & Radosevich 1986, White 1986, Petersen and Maxwell, 1987), there are no experimentally generated data which quantify the influence of artificial augmentation of soil moisture on competition. In an ongoing irrigation experiment we are testing the hypothesis that yield losses of conifer seedlings caused by woody weed competition can be substantially reduced by soil moisture augmentation during critical periods.

STUDY SITE AND METHODS

We initiated several experiments on neighborhood competition in Blodgett Forest Research Station (BFRS, El Dorado, Cal.) during 1986-9. Detail analyses of neighborhood competition is being conducted in three fenced control (no treatment) mixed plantations in compartment 370 of BFRS. Maps indicating canopy cover, height, and position of seedlings of nine naturally occurring shrub species in 170 permanent plots of 2.5 m radius centered on two-year-old planted seedlings of either *Pinus ponderosa* (ponderosa pine), *Sequoiadendron giganteum* (giant sequoia) or *Pseudotsuga menziesii* (Douglas-fir), all planted in 1985, were drawn in 1986. Stem diameter at 5 cm and height of all three conifers were measured in Oct. 1986, Nov. 1987, and Nov. 1988. Major woody weed species studied are greenleaf manzanita (*Arctostaphylos patula*), mountain whitethorn (*Ceanothus cordulatus*), Sierra gooseberry (*Ribes roezlii*), and bush chinquapin (*Castanopsis sempervirens*).

Digitized data from these maps were stored by a special program written in BASIC and rechecked after plotting on Macintosh ImageWriter. Employing another original program, eight different indices of neighborhood competition were then calculated (Rejmánek & Messina 1989). Angular or "sum of angles" competition index (fig. 1) derived from Lin's (1974) "growing space index" proved to be a most promising predictor of competition influences of woody weeds on ponderosa pine because the field data required are easily collected and the resulting predictions are not significantly different from predictions based on more sophisticated indices (Rejmánek & Messina 1989). Measurements of predawn leaf water potential and net photosynthesis rates expressed as a function of this index and other competition indices support this conclusion.

Predawn leaf water potential of conifer seedlings was measured using a Scholander pressure chamber (Scholander et al. 1965, Koide et al. 1989). Soil moisture was determined gravimetrically (Slavík 1974). Path analysis (Le Roy 1960, Kenny 1979) was used to suggest the most important direct and indirect cause-effect connections between the considered variables and the amount of variance accounted for by each.

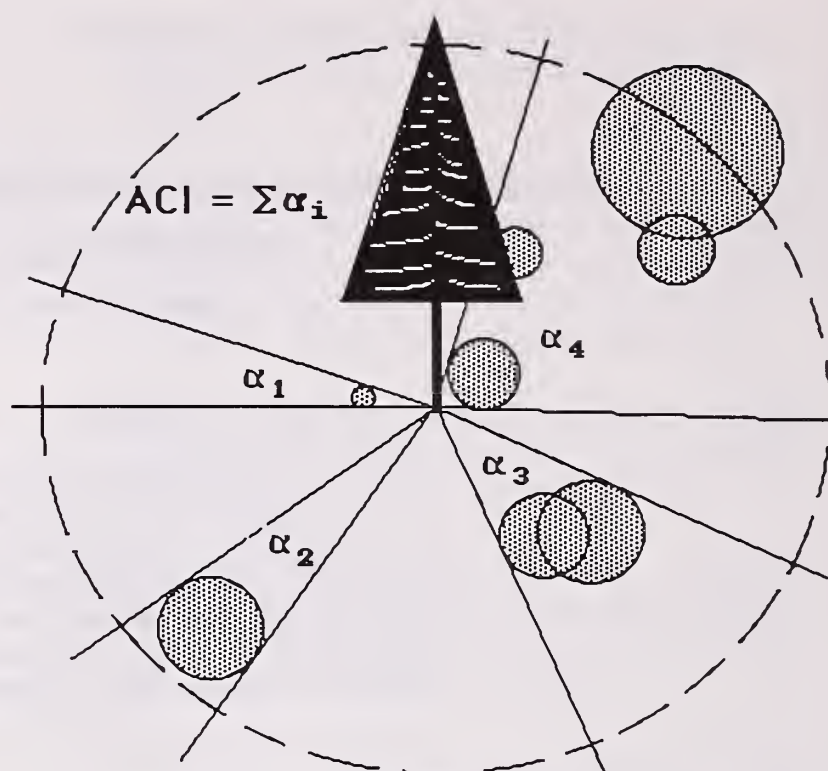


Figure 1.--Angular neighborhood competition index (ACI) is the sum of angles (α_i) formed by the two most distant edges of the individual plants or their aggregations and vertex corresponding to the position of a conifer seedling (the center of the picture). Individual competing plants (shrubs) are indicated as closed circles.

Eighty different permanent plots (BFRS, compartment 360) analyzed in 1987 were used for irrigation experiments in 1988 and 1989 to test the hypothesis that yield losses of ponderosa pine caused by woody weed competition can be substantially reduced by soil moisture augmentation during critical periods. A drip irrigation system was built to provide three experimental moisture regimes in 1988: control, low irrigation (once every 4 weeks, the amount corresponding to 80 liters per tree each irrigation) and high irrigation (once every 2 weeks). Only two moisture regimes were maintained during growing season 1989: control and irrigation (once every 2 weeks, the amount corresponding to 160 liters per tree each irrigation).

RESULTS AND DISCUSSION

With few exceptions, only the most abundant shrub species -- *Arctostaphylos patula* (greenleaf manzanita) -- contributed significantly to the regressions of relative diameter growth rate on angular competition index (fig. 2). The most significant regressions were obtained for ponderosa pine when data from plots of 2.0 or 2.5 m radius were used (fig. 3). Preliminary analyses of the root system of ponderosa pine seedlings helped to explain this result: lateral roots of ponderosa pine were up to 220 cm long in 1987. Regressions of conifer seedling height growth rate on the angular competition index were less significant and are not shown here.

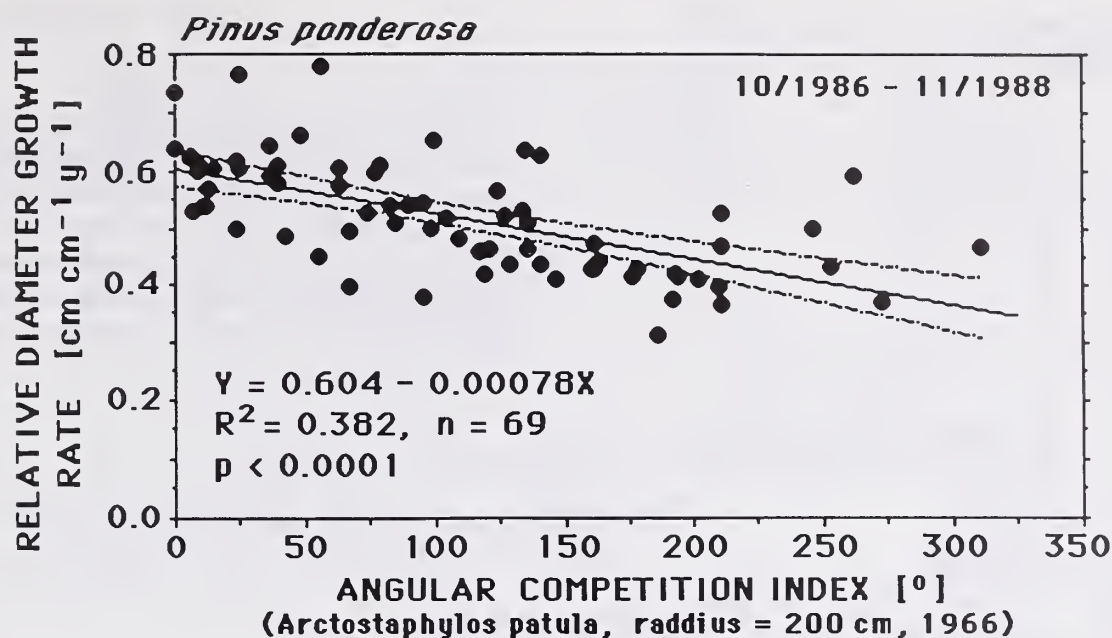


Figure 2.--Dependence of mean relative diameter growth rate of ponderosa pine over the period 10/1986 - 11/1988 on angular competition index (ACI) for greenleaf manzanita (*Arctostaphylos patula*) in plots of 200 cm radius analyzed in 1986. Dashed curves indicate 95% confidence bands for the true mean of Y.

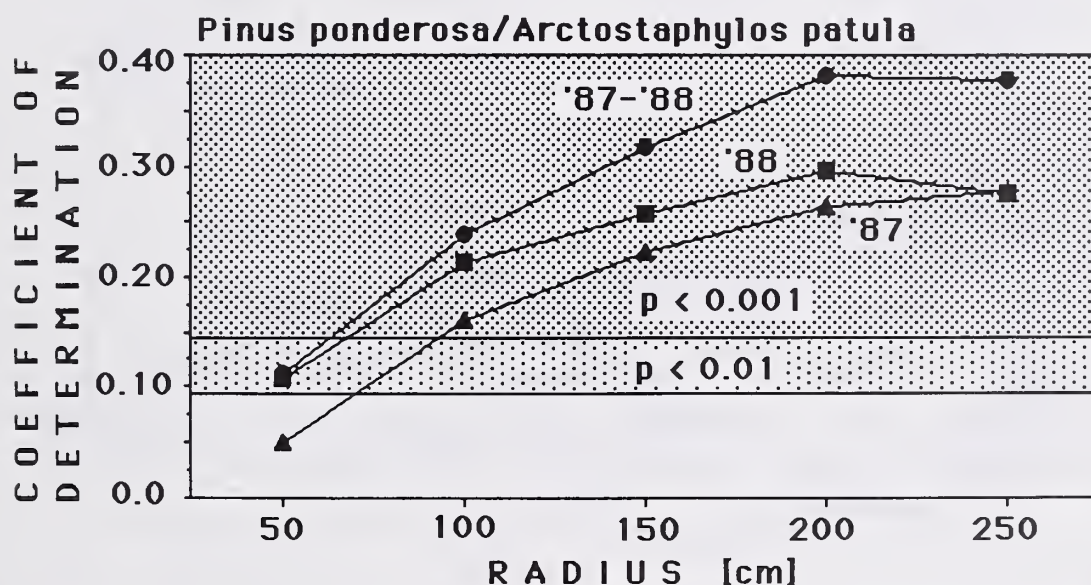


Figure 3.--Dependence of coefficient of determination (R^2), on the radius of sampled plots for the regressions of relative diameter growth rate of ponderosa pine on angular competition index (ACI) for greenleaf manzanita.

Not only growth of ponderosa pine seedlings was significantly negatively dependent on the angular competition index but soil moisture and predawn leaf water potential were significantly negatively dependent on this index as well (fig. 4). This dependence suggests that competition for soil water might be an important factor affecting the growth of ponderosa pine seedlings - a relationship hypothesized by many other authors. However, a simple path analysis (fig. 5) exploring the influence of soil moisture and predawn water potential indicated only negligible contribution of competition for soil moisture to the total competition influence of shrubs on ponderosa pine seedlings. Because most of the shrubs are much smaller than pine seedlings, competition for light can be excluded. The most plausible explanation therefore seems to be competition for some limiting nutrients.

The importance of soil moisture was directly evaluated in our irrigation experiment. Though physiological measurements (leaf water potential, stomatal conductance, net photosynthetic rate) suggested significant differences of stress in irrigated and non-irrigated pine seedlings during some intervals of both years of the experiment, there were no significant differences in relative stem diameter and height growth rates between irrigated and non-irrigated trees neither after the first nor after the second growing season (means of relative diameter growth rates for non-irrigated and irrigated trees over period 10/87 - 9/89 were 0.510 and 0.499 $\text{cm cm}^{-1} \text{y}^{-1}$ respectively). This result is surprising especially because both hydrological years - 1987/88 and 1988/89 were rather dry in California (precipitation at BFRS was 37 and 12% below the long-term average). However, since

both study sites have relatively deep soils (>1.5 m), the results may partly reflect this circumstance.

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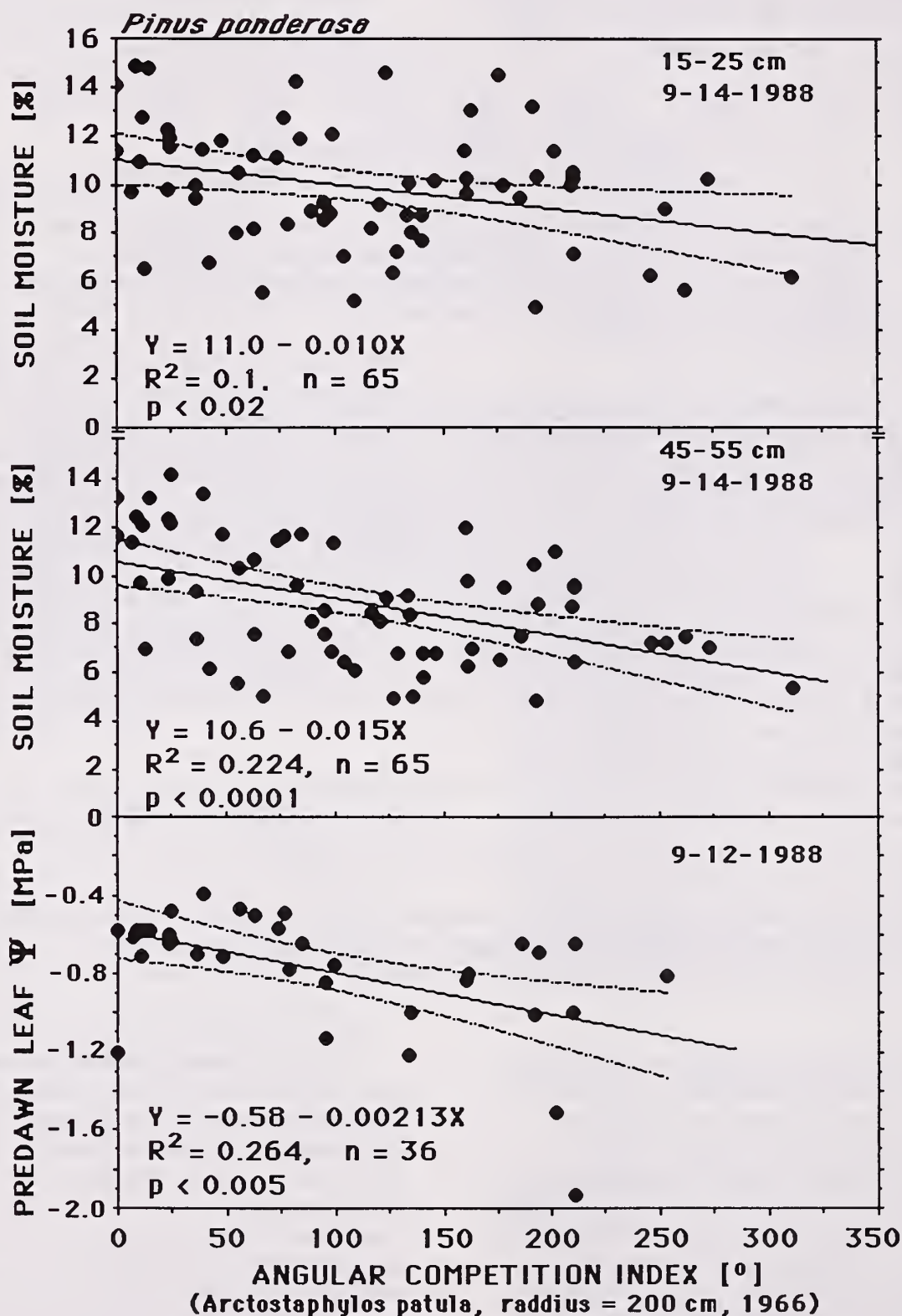


Figure 4.--Dependence of soil moisture (% by dry weight) and predawn leaf water potential of ponderosa pine on angular competition index for greenleaf manzanita in plots of 200 cm radius analyzed in 1986. Dashed curves indicate 95% confidence bands for the true mean of Y.

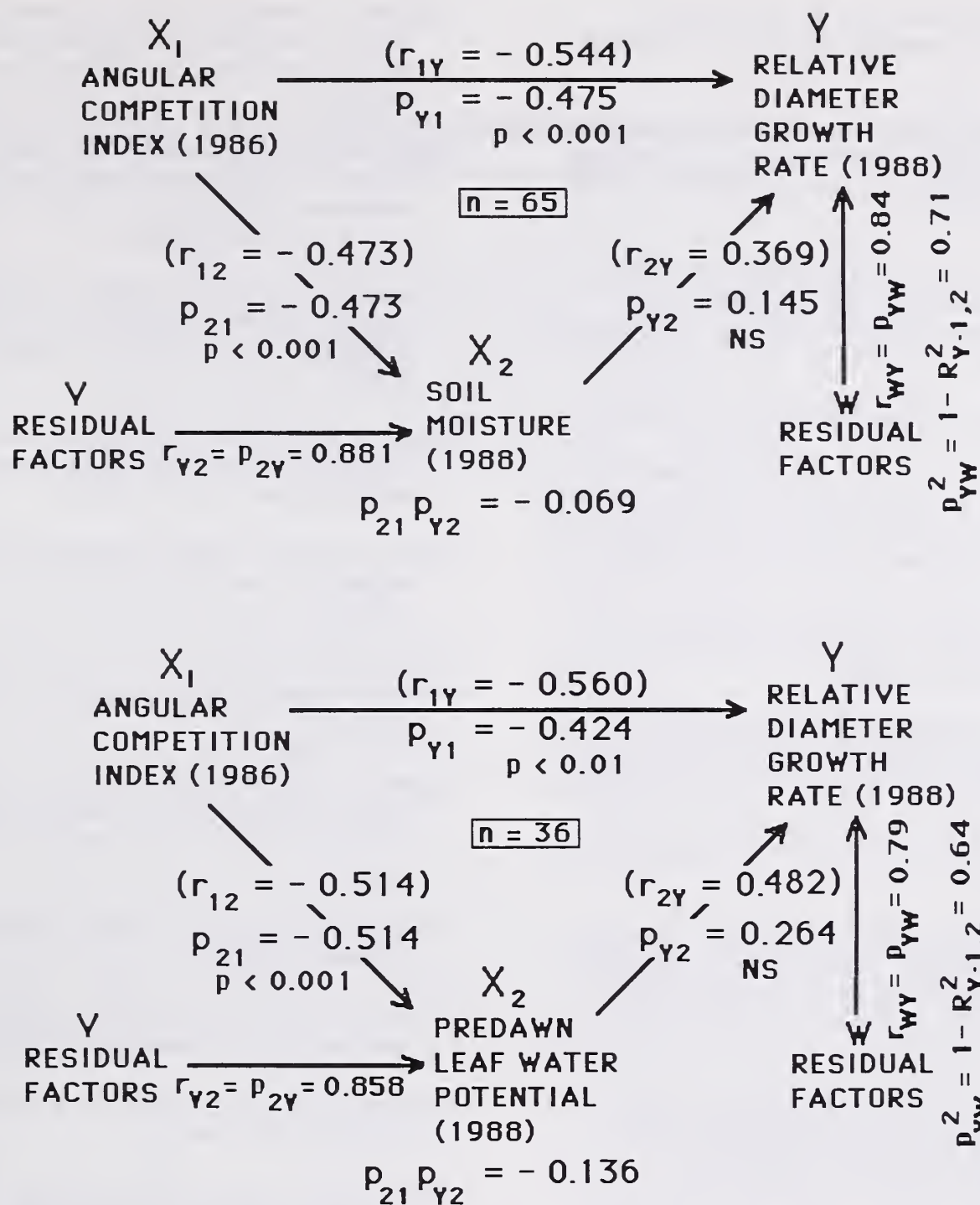


Figure 5.--Path diagram of the relationships between angular competition index (1986), soil moisture (1988) or predawn leaf water potential (1988), and relative diameter growth rate (1988). Path coefficients (p_{ij}) and products $p_{21}p_{Y2}$ in particular indicate rather weak indirect effect of X_1 on Y (through soil moisture or through leaf water potential).

LITERATURE CITED

- Averill, D., 1989. Tanoak coppice management. Proc. 10th Ann. For. Veget. Manag. Conf. (In press.)
- Axelsson, E. & B. Axelsson, 1986. Changes in carbon allocation patterns in spruce and pine trees following irrigation and fertilization. Tree Physiol. 2: 189-204.
- Brix, H., 1972. Nitrogen fertilization and water effects on photosynthesis and earlywood-latewood production in Douglas-fir. Canad. J. For. Res. 2: 487-478.
- Carter, G.A., J.H. Miller, D.E. Davis & R.M. Patterson, 1984. Effect of vegetative competition on moisture and nutrient status of loblolly pine. Can. J. For. Res. 14: 1-9.
- Craig, S. & J. McHenry, 1988. Mulch collars for preventing vegetation around conifer seedlings. Proc. 9th Ann. For. Veget. Manag. Conf., pp. 142-150.

- Firbank, L.G. & A.R. Watkinson, 1987. On the analysis of competition at the level of the individual plant. *Oecologia* 71: 308-317.
- Hegyi, F., 1974. A simulation model for managing jack-pine stands. In: J. Fries (Ed.): *Growth Models for Tree and Stand Simulation*. Royal College of Forestry, Research Notes No. 30, Stockholm, pp. 74-90.
- Jarvis, P.G., 1985. Increasing forest productivity and value of temperate coniferous forest by manipulating site water balance. In: R. Balard (Ed.) *Forest Potentials. Productivity and Value*. Weyerhaeuser. pp. 39-74.
- Kenny, D.A. 1979. *Correlation and Causality*. Wiley, New York.
- Koide, R. T., Robichaux, R.H., Morse, S.R. & C.M. Smith, 1989. Plant water status, hydraulic resistance, and capacitance. In: Pearcy, R.W. et al. (Eds.): *Physiological Plant Ecology: Field Methods and Instrumentation*. Chapman & Hall, London. pp. 161-183.
- Kramer, P.J. & T.T. Kozlowski, 1979. *Physiology of Woody Plants*. Academic Press. Orlando.
- Landsberg, J.J. 1986. Experimental approaches to the study of the effects of nutrients and water on carbon assimilation by trees. *Tree Physiol.* 2: 427-444.
- Le Roy, H.L. 1960. *Statistische Methoden der Populationsgenetik*. Birkhauser, Basel.
- Lin, J. Y., 1974. Stand growth simulation models for Douglas-fir and western hemlock in the northwestern U.S., pp. 102-18. In: J. Fries (Ed.): *Growth Models for Tree and Stand Simulation*. Royal College of Forestry, Research Notes No. 30, Stockholm.
- Lorimer, C.G., 1983. Tests of age-independent competition indices for individual trees in natural hardwood stands. *Forest Ecology and Management*. 6: 343-360.
- Newton, R.J., C.E. Meier, J.P. van Buijtenen & C.R. McKinley, 1986. Moisture-stress management: Silviculture and genetics. In: T.C. Hennessey (Ed.): *Stress Physiology and Forest Productivity*. Nijhoff, Dordrecht. pp. 35-60.
- Petersen, T.D. & B.D. Maxwell, 1987. Water stress of *Pinus ponderosa* in relation to foliage density of neighboring plants. *Can. J. For. Res.* 17: 1620-1622.
- Petersen, T.D., Newton, M. & S.M. Zedaker, 1988. Influence of *Ceanothus velutinus* and associated forbs on the water stress and stemwood production of Douglas-fir. *Forest Sci.* 34: 333-343.
- Radosevich, S.R., 1984. Interference between greenleaf manzanita (*Arctostaphylos patula*) and ponderosa pine (*Pinus ponderosa*). In: Duryea, M.L. & Brown, G.N. (Eds.). *Seedling Physiology and Reforestation*
- Rejmanek, M. & J.J. Messina, 1989. Predicting conifer growth reduction from the analysis of neighborhood weed competition. *Proc. 10th Ann. For. Veget. Mgmt. Conf.* pp. 79-93.
- Rejmanek, M., Robinson, G.R. & E. Rejmankova, 1989. Weed-crop competition: experimental designs and models for data analysis. *Weed Sci.* 37: 276-284.
- Sands, R. & E.K.S. Nambiar, 1984. Water relations of *Pinus radiata* in competition with weeds. *Can. J. For. Res.* 14: 233-237.
- Scholander, P., H. Hammel, E. Bradstreet and E. Hemmingsen, 1965. Sap pressure in vascular plants. *Science* 148: 339-346.
- Shainsky, L.J. & S.R. Radosevich, 1986. Growth and water relations of *Pinus ponderosa* seedlings in competitive regimes with *Arctostaphylos patula* seedlings. *J Appl. Ecol.* 23: 957-966.
- Slavík, B., 1974. *Methods of Studying Plant Water Relations*. Academia, Prague.
- Silander, J.A. & S.W. Pacala, 1985. Neighborhood predictors of plant performance. *Oecologia* 66: 256-263.
- Smith, B., 1989. Tanoak control. *Proc. 10th Ann. For. Veget. Manag. Conf* (In press.)
- Stewart, R.E., Gross, L.L. & B.H. Honkala, 1984. *Effects of Competing Vegetation on Forest Trees: A Bibliography with Abstracts*. USDA Forest Service, Washington, D.C.
- Weiner, J., 1984. Neighborhood interference amongst *Pinus rigida* individuals. *J. Ecol.* 72: 183-195.
- White, D.E., 1986. Effects of whiteleaf manzanita on Douglas-fir and ponderosa pine: Water use Strategies and growth. *Proc. 7th Annual Forest Veget. Manag. Conf.* pp.86-90.

Site Quality Estimates for Southwestern Ponderosa Pine¹

William F. Stansfield and John P. McTague²

Abstract.-- In the Southwest site quality is generally estimated with site index. Other methods of estimating site quality from soil-site and plant community relationships are generally related back to site index; however their utilization in the southwest has been limited. Estimates of site index may be refined by including ancillary variables in the dominant height and site index equations.

INTRODUCTION

Site quality is defined by Clutter and others (1983) as the timber production potential of a site for a particular species or forest type. Estimates of site quality are generally obtained by estimating site index. However, estimates of site quality may also be obtained from soil-site relationships, and plant community relationships.

Several methods have been utilized to investigate site quality for ponderosa pine in the Southwest: site index, soil-site, and habitat type relations. The objective of this paper is to discuss such studies and examine them in regards to estimating potential productivity of a site.

SITE INDEX

Site index is commonly defined as the height of the average dominant tree at a specified index age. Thus, site index provides a quantitative estimate of site quality at a given point in time. In order to estimate site index at ages other than the index age, site index curves are developed. Such curves depict the expected average dominant height develop-

ment pattern of the stand for a given site index (Clutter et al., 1983). In the Southwest site index curves developed by Meyer (1938) and Minor (1964) have been used.

The Meyer (1938) site index curves (fig. 1) are anamorphic; that is the system of curves all have the same shape, but differ in height by a constant ratio (Spurr, 1952). The height and age data

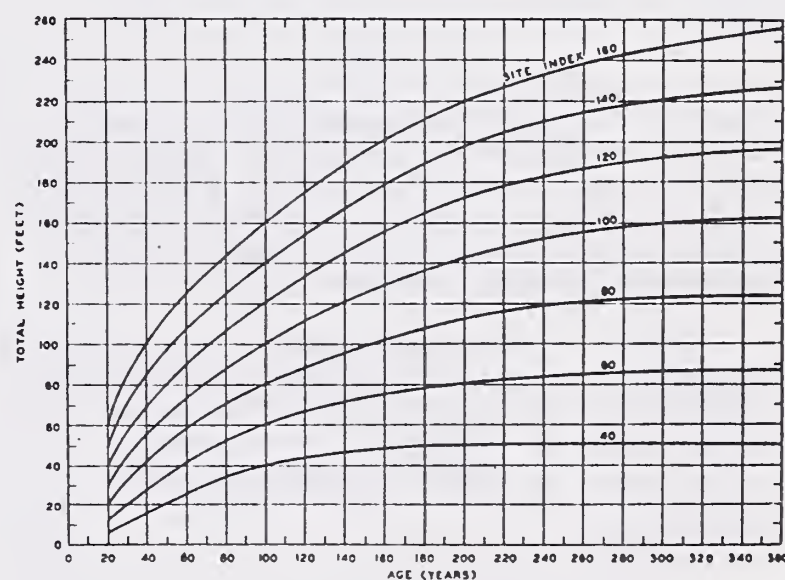


Figure 1.-- Anamorphic site index curves developed by Meyer (1938) for ponderosa pine.

used to construct these curves were obtained from temporary plots throughout the west. However, no data were obtained from Arizona or New Mexico.

In addition to the apparent problem of having no data from the Southwest, these curves are plagued by the problems of utilizing data from temporary plots to construct anamorphic site index curves.

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²William F. Stansfield was Research Assistant, Northern Arizona University, Flagstaff, AZ; currently Forester with SWCA, Environmental Consultants, Flagstaff, AZ. John Paul McTague is Associate Professor of Forest Biometrics, School of Forestry, Northern Arizona University. Flagstaff, AZ.

Inherent assumptions in the construction technique are (Spurr and Barnes, 1980):

- 1) The average site index is the same for each age class.
- 2) The dominant height growth rate is the same for all sites.

The first assumption implies that site index is not correlated with age. It has been noted (Beck, 1971a and Carmen, 1975) that often better quality sites will be supporting younger growing stock while poorer sites will be supporting older growing stock. Such a condition may exist due to past harvesting. In such instances site index is correlated with age, and the anamorphic site index curve, derived from temporary data, will be distorted and negatively correlated with age. Thus site index will be overestimated for young stands and underestimated for old stands. The second assumption implies that the rate of growth is the same for all sites. Several investigators have observed that this assumption is in error (Bull, 1931; Beck, 1971; and Carmean, 1972). On high quality sites the rate of height growth is typically greater for young dominant trees and tends to decrease as the tree ages. In contrast, young trees growing on low quality sites tend to have slower initial height growth. However, as age increases the growth rates for trees on high and low quality sites tend to converge (Beck, 1971a).

In order to avoid the assumptions of anamorphism and the associated errors, real growth data is commonly employed in the construction of site index equations. Such data may be obtained from permanent plot remeasurements, stem analysis or internode measurements.

Minor (1964) developed polymorphic site index curves with real growth data obtained from north-central Arizona using stem analysis (fig. 2). Polymorphic curves are a family of curves which display different shapes for varying site qualities.

Minor (1964) utilized the parameter prediction method to construct a dominant height equation. The dominant height equation is expressed as:

$$H = S - 1.4003 (A^{.5} - 10) + 0.1559 (S) (A^{.5} - 10) \quad (1)$$

where

H = dominant height
S = site index
A = age at breast height in years.

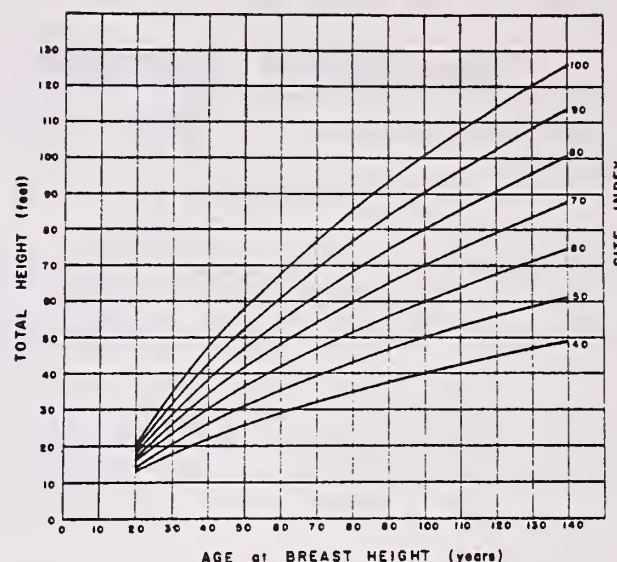


Figure 2.-- Polymorphic site index curves developed by Minor, 1964 for southwestern ponderosa pine.

The site index equation is obtained by inverting the dominant height equation such that site index becomes the dependent variable:

$$S = \frac{H + 1.4002(A^{.5} - 10)}{1 + 0.1559(A^{.5} - 10)} \quad (2)$$

Examination of equation (2) reveals that it is consistent with the definition of site index. When age at breast height equals the reference age of 100, dominant height and site index are equivalent. The curves produced, however, do not have an upper asymptote, and therefore are not recommended for use on trees greater than 150 years old.

The methodology utilized in the construction of dominant height and site index equations dictates their use in the field. Several salient features of the Minor site index curves deserve mention.

- 1) The site index equations are fitted to individual trees and not to an average tree per plot. Thus, the average site index of a stand is computed by determining a value of site index for each tree measured, and then by calculating a mean of the site index values.
- 2) Unlike most site index curve, the Minor equations are constructed from trees in only the dominant crown class. Therefore, codominants should not be selected as site trees. There is no need, however, to measure the tallest dominant tree in the stand. In addition, trees selected may be in dense clumps or isolated, since stand density does not have a significant

effect on dominant height (Minor, 1964; and Stansfield, 1989).

- 3) Minor used age at breast height rather than total age for the site index relationship. This procedure reduces the error found in other site index curves that arbitrarily correct for the number of years from stump to breast height.

Presently, all of the growth and yield simulators available in the southwest utilize site index as a driving variable. Three of the four simulators are calibrated to Minor's (1964) site index curves. RMYLD (Edminster, 1978) does calculate the average height of stand dominants and codominants to determine yield. The average height of dominants and codominants is calculated as a piece-wise function of total age and site index. The estimates of site index are obtained from Hornibrook's (1939) study of Black Hills ponderosa pine. Myer (1971) provided the following expressions:

$$\begin{aligned} &\text{for age less than 55} & (3) \\ H = & 0.1441(A)(S) - .12162(A) - 1.50953, \end{aligned}$$

$$\begin{aligned} &\text{for age greater than 55} & (4) \\ H = & 10 (0.59947 - 61.5019/A + 0.80522 \\ & (\text{Log } S) + 20.525218 (\text{Log } S)/A \end{aligned}$$

where

H = average height of dominant and codominant trees
S = site index
A = total age.

Utilization of equations (3) and (4) require the analyst to determine site index based on Hornibrook (1939), and not Minor (1964).

Site index, provides a quantitative approach to examine site quality, and uses the tree to integrate the factors which are required for growth. However, stand conditions may be such that estimates of site index are unreliable. Therefore, other methods that utilize soil-site factors or understory vegetation are also utilized to estimate site quality.

SOIL-SITE FACTORS

Relatively little research has been directed toward quantifying the effects of soil-site factors on site quality in the Southwest. In general, factors which are examined influence the availability of moisture and nutrients, as well as the trees physiological and evapotranspiration processes (Carmean, 1975). Coile (1938) suggested that aspect, slope, topographic position, texture and thick-

ness of the A and B horizons, parent material and depth of the soil be considered when examining site quality. In addition, it is desirable that factors examined be readily identifiable in the field.

Williams et al., (1963) examined the effects of parent material, and chemical and physical properties of seven soils from the Zuni Mountains of New Mexico in regards to timber production. Williams et al., (1963) found that greenhouse fertility, surface permeability combined with depth of permeable soil, and available moisture-holding capacity of the surface soil were correlated with site index. Soils with high fertility, water-holding capacity, permeability of the A horizon and depth of the permeable soil had higher site index.

Senn (1976) examined site index in regards to soil type and parent material. Frequency distribution curves (fig. 3), developed by Senn (1976), for a range of site indices illustrate that site index variability for igneous soils in the Salt-Verde River Basin is related to

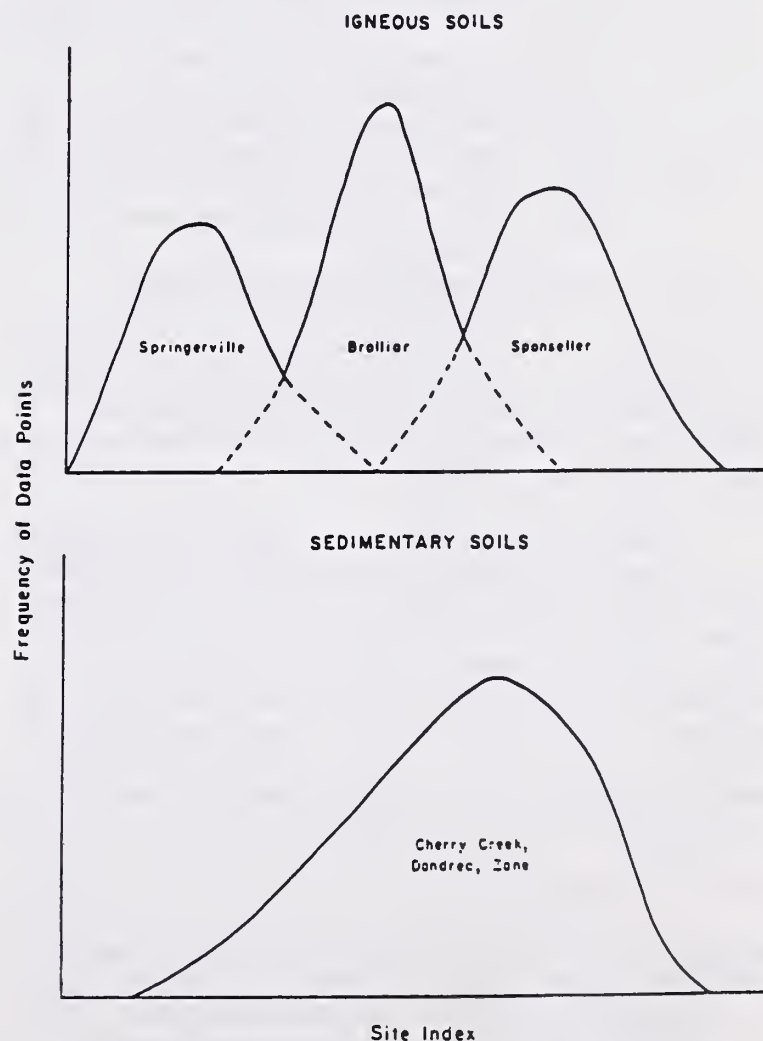


Figure 3.-- Relationship between site index and soil type (Senn, 1976).

differences in soil properties such as soil depth, infiltration capacity, and rockiness. As illustrated (fig. 3), distributions overlap at the lower frequency levels. Senn (1976) concludes that site index variation for sedimentary soil is not evident between soil types but rather within soil types. The site index variability is attributed to physiographic characteristics such as slope, aspect and elevation.

Minor³ examined 18 soil-site factors and their relation to site index. He developed three linear models dependent upon parent material: sandstone, Kaibab Limestone, and Basic Igneous. The equations for each parent material are presented below.

$$\text{Sandstone } R^2 = 0.46 \quad (5)$$

$$SI = 67.17 + 0.349(TH_{A+B}) - 0.163(SL)$$

$$\text{Kaibab Limestone } R^2 = 0.58 \quad (6)$$

$$\text{Log SI} = 1.553 + 0.159(\text{Log } TH_A) + 0.143(\text{Log } WP)$$

$$\text{Basic Igneous } R^2 = 0.38 \quad (7)$$

$$SI = 85.41 + 0.476(TH_{A+B}) - 203.1(1/SP)$$

where

SI = Site Index in feet
(Minor, 1964)
TH_{A+B} = Thickness of the A and B horizon (inches)
TH_A = Thickness of the A horizon (inches)
SL = Position on slope from base to top (%)
WP = Winter Precipitation (inches)
SP = Summer Precipitation (inches).

The explained variation provided by these equations are typical of soil-site regression equations used to estimate site index (Carmean, 1975).

Verbyla and Fisher (1989a) developed soil-site equations to estimate site index (index age 25). They advocate stratified random sampling for high and low quality sites will produce greater precision in estimating site quality from soil site factors. In their study they determined high quality sites to be from cool-moist habitat types with a high percent sand and a soil ph at 15 cm less than 6.55.

Verbyla and Fisher examined 32 possible variables including: aspect, solar radiation, elevation, as well as additional soil descriptors. However the final model for high quality sites, equation (8), was reduced to four variables and produced an adjusted R² of 0.49.

$$SI = 8.587 + 0.35(SA) - 0.064(SL) + 0.091(SI) - 0.009(P) \quad (8)$$

where

SA = Percent sand at 15 cm
SL = Percent slope
SI = Percent silt at 45 cm
P = Extractable phosphorus at 15 cm.

Brown and others (1974) have provided information concerning mean annual increment of ponderosa pine sawtimber yields for Broillear and Siesta Sponseller soil types. Based on the results of simulation runs from PIPO, a growth and yield simulator, (Larson, 1975) sawtimber growth rates on Siesta Sponseller soils are more than twice that of Broillear soils over a range of basal areas 40 to 120 sq. ft. acre.

Larson and Minor (1983) have included soil type, based on parent material in an equation for predicting individual trees heights as a function of diameter at breast height and site index. The equation is:

$$H = 4.5 + b_0 (1.9026(D) + 0.0287(D)(S)) - b_1 (0.0403(D^2) (S - 70)^2) \quad (9)$$

where

H = total individual tree height in feet
D = dbh in inches
S = Minor's site index
b₀ = 0.892 basalt soil
0.964 limestone soil
1.143 sandstone soil
b₁ = 0.740 basalt soil
0.688 limestone soil
1.300 sandstone soil

This equation produces greatest heights, for a give site index, on soils derived from sandstone parent material. Heights for basalt soils are typically the lowest, while limestone soils produce heights that are in the middle.

³Minor, C. O. Unpublished research work. Soil-site site index equations for ponderosa pine based on parent material. personal communication. September. 1989. Flagstaff, AZ.

HABITAT TYPES

A habitat type is the collective area which is capable of supporting the same climax vegetation (Daubenmire, 1961). It is the basic unit in a site classification

system (Alexander, 1985) that utilizes the plant community as an integrator of environmental factors (Pfister, 1976). For timber management, habitat types have been suggested as indicators of site quality, silvicultural prescriptions, and physical and biological hazard ratings (Daubenmire, 1976).

Youngblood and Maulk (1985) delineated habitat types for ponderosa pine in southern and central Utah by productivity potential. Schubert (1974) has classified southern and central Utah into the Colorado Plateau physiographic province for southwestern ponderosa pine. Univariate statistics for site index by habitat type were provided. The mean site index and 95% confidence intervals for ponderosa pine are graphically displayed in figure 4. Inspection of means and

confidence intervals suggests that the difference in site index between habitat types is marginal. However, an analysis of variance and multiple range test must be performed to validate this hypothesis.

For southwestern ponderosa pine in New Mexico and Arizona, Mathiasen et al. (1987) did not find significant differences in mean site index between habitat types based on analysis of variance and multiple range tests. In a similar study, Mathiasen et al. (1986) found that mean site index for southwestern Douglas-fir in ten habitat types differed significantly, and that the habitat types could be separated into three distinct site quality classes. It should be noted that in each of Mathiasen's studies, both dominants and codominants were used to obtain site index estimates from the published curves. However, Minor's curves (1964) and Edminster and Jump's curves (1976) were constructed with only dominant trees. It is possible that by including codominants, site indices were underestimated and variances of the estimates were increased. In addition, Mathiasen et al. (1987) erroneously computed mean site index by averaging dominant heights and ages of the sample trees and computing a single site index estimate, rather than obtaining the site index of each individual tree and then averaging. If site trees were selected and calculations performed in a manner consistent with the construction of the site index curves, more definitive results might have been obtained.

Verbyla and Fisher (1989b) examined five habitat types in southern Utah in regards to ponderosa pine site index (base age 25). They found mean site index differed significantly among the five habitat types. They observed that the best ponderosa pine sites (site index greater than 7.2 m) occurred in the Pinus ponderosa/Quercus gambelii and Pinus ponderosa/Symphoricarpos oreophilus habitat types. However, within habitat type variation of site indices were broad, and therefore they recommended that habitat type should not be used alone in predicting the best ponderosa pine sites.

Daubenmire (1976) suggested that the shape of the dominant height curve may differ between habitat types. Monserud (1984) considered this hypothesis for Douglas-fir in the Inland empire; however, his data were obtained by habitat series. Monserud's results demonstrated that the shape of the dominant height curve did vary between habitat series, however, the differences were slight for stands under 70 years.

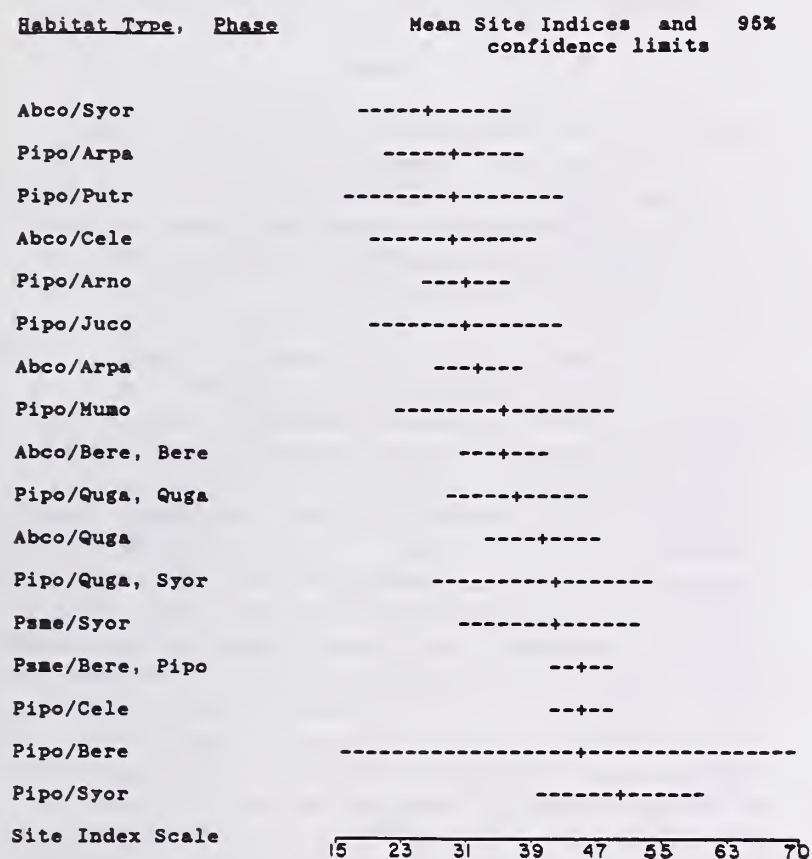


Figure 4.-- Ponderosa pine mean site indices and 95% confidence limits by habitat type for southern and central Utah. Data from: Youngblood and Maulk, 1985.

^aReference age is 50.

^b"+" denotes the mean site index for each habitat type.

^c the broken line represents the 95% confidence limits centered about the mean.

Stansfield (1989), similar to Monserud (1984), developed dominant height and site index equations for ponderosa pine on the Fort Apache Indian Reservation, in east-central Arizona. The equations incorporate habitat type groups and administrative unit as dummy variables. The dominant height equation was constructed from a sample of 147 dominant trees that were selected from 11 habitat types. The height/age pairs of each tree were determined with stem analysis, and fit to the King linear model, which contains three parameters. These parameters were then related to site index, habitat type groups and administrative unit. The dominant height equation is:

$$H = A^2 / C_1 + [(10000 / (S - 4.5)) \{C_2 + (X_4 * C_3) + (X_1 * C_4) + (X_2 * C_5) + (X_3 * C_6)\}] \quad (10)$$

where

H = dominant height in feet

A = age at breast height in years

S = site index (base age 100)

$C_1 = (-0.2937434511 - 0.25181744172 * A + 0.00254798987 * A^2)$

$C_2 = (0.18412315645 + 0.00476897243 * A + 0.00003392903 * A^2)$

$C_3 = (-0.0665378094 + 0.00121985862 * A + 0.00005543764 * A^2)$

$C_4 = (-0.0708831617 + 0.00129952334 * A + 0.000005905808 * A^2)$

$C_5 = (0.03261381732 - 0.001413265 * A + 0.0000108721 * A^2)$

$C_6 = (-0.0413267842 + 0.00179908267 * A + 0.0000137767 * A^2)$

$X_1 = 1$ if habitat type is Pipo/Qugr
Pipo/Mumo
0 otherwise

$X_2 = 1$ if habitat type is Pipo/Qugr,
Pipo/Quga or Pipo/Mumo
0 otherwise

$X_3 = 1$ if habitat type is Pipo/Fear,
Pipo/Muvi, Psme/Quhy, Psme/
Fear, or Psme/Muvi
0 otherwise

$X_4 = 1$ if administrative unit is
Northwest or Tribal
0 otherwise.

The site index equation is obtained by inverting the dominant height equation such that site index becomes the dependent variable. The equation may be expressed as:

$$S = 10000(H - 4.5) \{C_2 + (X_4 * C_3) + (X_1 * C_4) + (X_2 * C_5) + (X_3 * C_6)\} / [A^2 + (H - 4.5) * C_1] \quad (11)$$

where

all variables are as previously defined.

Figure 5 illustrates the dominant height relationship for ponderosa pine on the Southwest, Northfork and Maverick administrative units of the Fort Apache Indian Reservation for Pipo/Qugr and Pipo/Mumo habitat types.

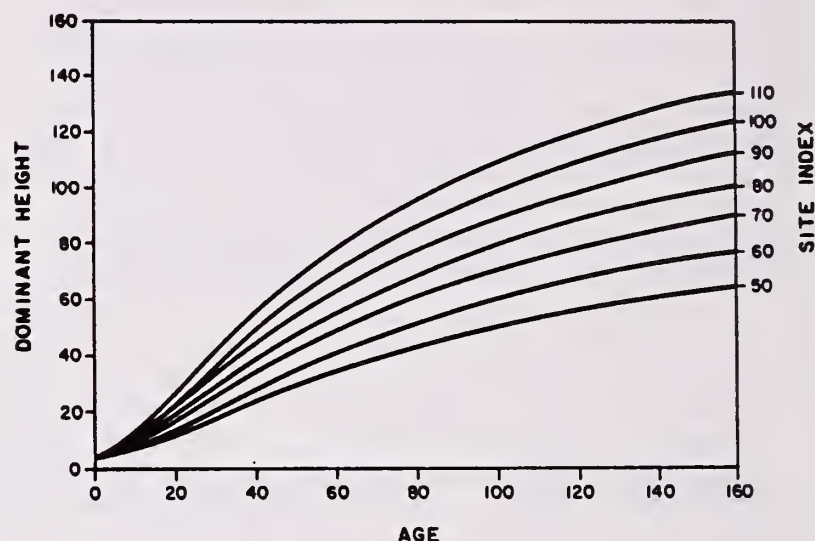


Figure 5.-- Ponderosa pine site index curves for the Fort Apache Indian Reservation (Habitat types Pipo/Qugr, and Pipo/Mumo; and Southwest, Northfork, and Maverick administrative units).

The ancillary variables, habitat type and administrative unit, assist in refining the dominant height curve by establishing different growth rates for any given site index. The effect of habitat type group on the dominant height curve for site index 80 is demonstrated in figure 6. Differences in growth rates are evident at age 20 and reach a maximum at age 50, approaching four feet. Beyond age 50 the growth curves converged at age 100. This behavior is consistent with the definition of site index. Beyond age 100 the growth curves diverge rapidly. The effects of administrative unit for Pipo/Qugr and Pipo/Mumo are illustrated in figure 7. Between administrative groups the difference in dominant height (site index 100) approached four feet at age 30. This difference continued although it was smaller at age 70. On lower quality sites the difference was less dramatic and converged slightly earlier.

SUMMARY AND CONCLUSIONS

Site index is the primary method used in the Southwest to evaluate site quality. Minor's (1964) polymorphic equations are

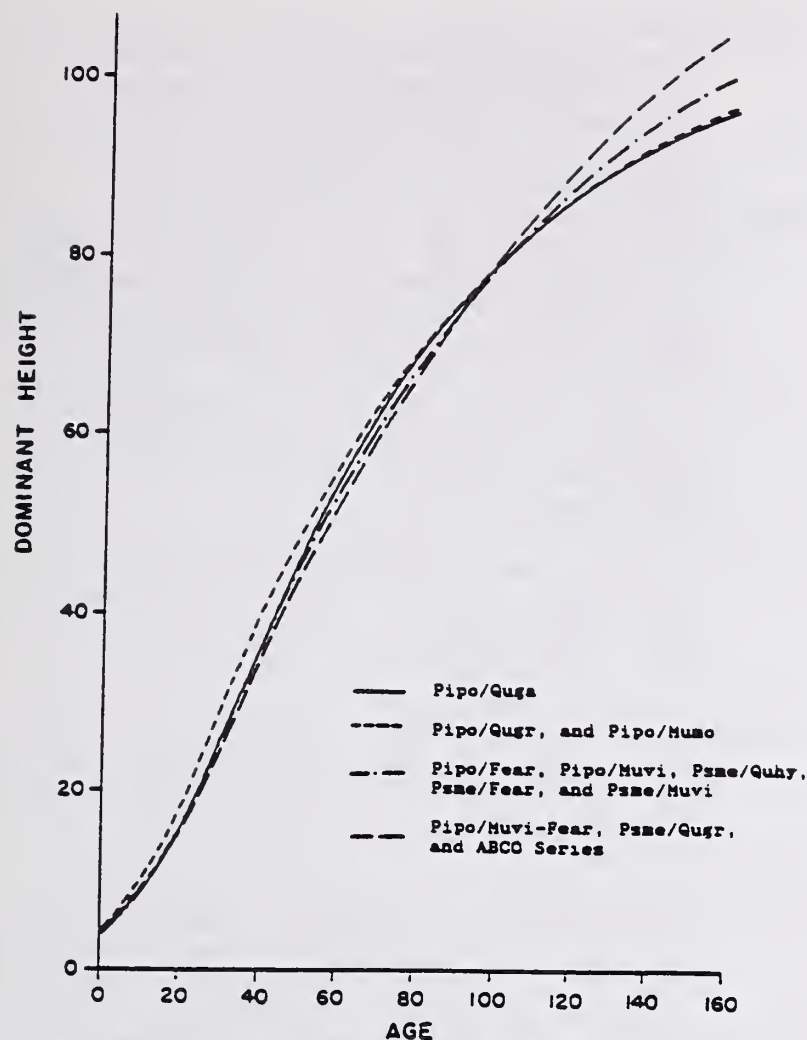


Figure 6.-- Ponderosa pine site index curves for the Fort Apache Indian Reservation (site index 80 - all habitat types groups; and Southwest, Northfork, and Maverick administrative units).

the primary dominant height and site index equations used. However, site index and dominant height may be estimated with Meyer (1938) and the routine in RMYLD (Edminster, 1978). The latter methods are of limited utility since they were developed outside of the Southwest. The Meyer site index curves (1938) are also plagued by the assumptions of anamorphism as discussed previously.

Soil-site studies in the Southwest have generally attempted to regress soil and site characteristics to site index. Limited success has been realized by Minor (unpublished) and Verbyla and Fisher (1989). From the studies performed, the most important characteristics utilized in such studies infer the importance of moisture availability on a site. Examination of the sites water balance would be a useful to quantify the sites potential productivity. However, it is of limited practicality on an operational basis, due to the measurements needed to derive the water balance.

The use of habitat types in the southwest has been extensively examined.

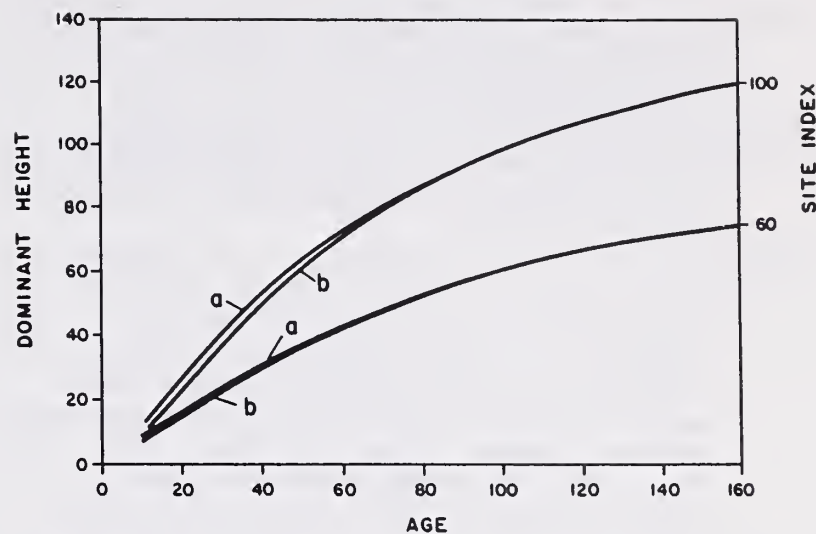


Figure 7.-- Ponderosa pine site index curves for the Fort Apache Indian Reservation (Habitat types Pipo/Qugr and, Pipo/Mumo by administrative unit).

^aNorth section west unit and Tribal unit.

^bSouth section west unit, Northfork and Maverick units.

Investigators (Matheisian et al. , 1987; and Verbyla and Fisher, 1989) have not been successful in correlating individual habitat types with site index. Typically, the range of site indices within a habitat type are broad. However, groups of habitat type have been useful as dummy variables in describing the dominant height curve and estimating site index by identifying differences in growth rates (Stansfield, 1989).

One can expect that site index will continue to be the primary mechanism used to evaluate site quality. Use of ancillary variables that better define the growth curve should be included in future site index and dominant height equations. In the Southwest subdivisions within the Terrestrial Ecosystem Survey may be potentially important ancillary variables that can allow one to better evaluate site index and thus site quality.

LITERATURE CITED

- Alexander, R. R. 1985. Major habitat types, community types, and plant communities in the Rocky Mountains. USDA For. Serv. Gen. Tech. Rpt. RM-123, 105 p. Rocky Mountain For. and Range Exp. Stn., Fort Collins, CO.

- Beck, D. E. 1971a. Polymorphic site index curves for white pine in the southern Appalachians. USDA For. Serv. Res. Pap. SE-80, 8 p. Southeast For. Exp. Stn., Asheville, NC.
- Beck, D. E. 1971b. Height-growth patterns and site index of white pine in the southern Appalachians. For. Sci. 17:252-260.
- Bull, H. 1931. The use of polymorphic curves in determining site quality in young red pine plantations. J. Agri. Res. 43:1-29.
- Brown, H. E., M. B. Baker, J. J. Rogers, W. P. Clary, J. L. Kovner, F. R. Larson, C. C. Avery, and R. E. Campbell. 1974. Opportunities for increasing water yields and other multiple use values on ponderosa pine forest lands. USDA For. Serv. Res. Pap. RM-129. Rocky Mountain For. and Range Exp. Stn., Fort Collins, CO.
- Carmean, W. H. 1972. Site index curves for upland oaks in the Central States. For. Sci. 18:109-120.
- Carmean, W. H. 1975. Forest site quality evaluation in the United States. Adv. in Agronomy. 27:209-269.
- Coile, T. S. 1938. Forest classification: classification of forest sites with special reference to ground vegetation. J. For. 36:1062-1066.
- Daubenmire, R. 1961. Vegetative indicators of rate of height growth in ponderosa pine. For. Sci. 7:24-34.
- Daubenmire, R. 1976. The use of vegetation in assessing the productivity of forest lands. Bot. Rev. 42:115-143.
- Edminster, C. B. and L. H. Jump. 1976. Site index curves for Douglas-fir in New Mexico. USDA For. Serv. Res. Note RM-326, 4 p. Rocky Mountain For. and Range Exp. Stn., Fort Collins, CO.
- Edminster, C. B. 1978. RMYLD: computation of yield tables for even-age and two storied stands. USDA For. Serv. Res. Pap. RM-199. Rocky Mountain For. and Range Exp. Stn., Fort Collins, CO.
- Hornibrook, E. M. 1939. Preliminary yield tables for selectively cut stands of ponderosa pine in the Black Hills. J. For. 37:807-812.
- Larson, F. R. 1975. Simulating growth and management of ponderosa pine stands. Ph. D. dissertation. Colorado State University, Fort Collins, CO. 118 p.
- Larson, F. R. and C. O. Minor. 1983. AZPIPO; a simulator for growth and yield of ponderosa pine in Arizona. Arizona Forestry Notes No. 20. School of Forestry, Northern Arizona University, Flagstaff, AZ.
- Mathiasen, R. L., E. A. Blake, and C. B. Edminster. 1986. Estimates of site potential for Douglas-fir based on site index for several southwestern habitat types. Great Basin Naturalist. 46:277-280.
- Mathiasen, R. L., E. A. Blake, and C. B. Edminster. 1987. Estimates of site potential for ponderosa pine based on site index for several southwestern habitat types. Great Basin Naturalist. 47:467-472.
- Meyer, W. H. 1938. Yield of even-aged stands of ponderosa pine. USDA Tech. Bull. No. 630, 59 p. Washington, D. C.
- Minor, C. O. 1964. Site index curves for young-growth ponderosa pine in northern Arizona. USDA For. Serv. Res. Note RM-37, 8 p. Rocky Mountain For. and Range Exp. Stn., Fort Collins, CO.
- Monserud, R. A. 1984b. Height growth and site index curves for inland Douglas-fir based on stem analysis data and forest habitat type. For. Sci. 30: 943-965.
- Myers, C. A. 1971. Field and computer procedures for managed-stand yield tables. USDA For. Serv. Res. Pap. RM-79, 24 p. Rocky Mountain For. and Range Exp. Stn., Fort Collins, CO.
- Pfister, R. D. 1976. Land capability assessment by habitat type. In: America's Renewable Resource Potential - 1975: The Turning Point. Proceeding, 1975 National Convention, Society of American Foresters, pg. 312-325. September 28 - October 2, 1976. Washington, D. C.
- Senn, R. A., Jr. 1976. A descriptive inventory of ponderosa pine on national forest in the Salt-Verde Basin, Arizona. USDA For. Serv. Gen. Tech. Rpt. RM-26. Rocky Mountain For. and Range Exp. Stn., Fort Collins, CO.
- Schubert, G. H. 1974. Silviculture of southwestern ponderosa pine. The status of our knowledge. USDA For. Serv. Res. Pap. RM-123, 71 p. Rocky Mountain For. and Range Exp. Stn., Fort Collins, CO.
- Spurr, S. H. 1952. Forest Inventory. The Ronald Press Co. New York. 476 p.
- Spurr, S. H. and B. V. Barnes. 1980. Forest Ecology. 3rd ed. John Wiley and Sons. New York. 687 p.
- Stansfield, W. F. 1989. Dominant height and site index equations for ponderosa pine on the Fort Apache Indian Reservation. Unpublished Thesis. Northern Arizona University, Flagstaff, AZ. 128 p.

- Williams, J. A., A. A. Levan, and H. E. Dregne. 1963. Relation of soil properties to ponderosa pine production in the Zuni Mountains, New Mexico. Proceedings of 2nd North American Forest Soils Conference, Corvallis, OR. pp. 381-398.
- Verbyla, D. L. and R. F. Fisher. 1989a. An alternative approach to conventional soil-site regression modeling. Can. J. For. Res. 19:179-184.
- Verbyla, D. L. and R. F. Fisher. 1989b. Ponderosa pine habitat types as an indicator of site quality in the Dixie National Forest, Utah. West. J. Appl. For. 4:52-54.
- Youngblood, A. P. and R. L. Mauk. 1985. Coniferous forest habitat types of central and southern Utah. USDA For. Serv. Gen. Tech. Rep. INT-187, 80 p. Intermountain For. and Range Exp. Stn, Ogden, UT.

Methods for Testing the Wessin Variant of PROGNOSIS: Sensitivity to Simulated Ozone¹

Terry D. Droessler²

Abstract.--The Western Sierra Nevada PROGNOSIS variant (WESSIN) projects tree and stand growth and yield for mixed-conifers in California. Elevated ambient ozone levels cause premature needle senescence with the greatest effects in the older needles of the lower crown. WESSIN growth equations contain live crown ratio as a predictor variable. Equation forms and parameter signs indicate how the model may perform in extreme conditions. WESSIN may also be tested by projecting ponderosa pine diameter growth, height growth and mortality for four 10-year cycles using four hypothetical live crown ratio levels in addition to the control.

INTRODUCTION

This work addresses methods to simulate ozone effects on ponderosa pine. The objective was to test the potential of WESSIN for simulating ozone damage via the live crown ratio variable.

The stand growth and yield model PROGNOSIS (Stage 1973; Wykoff 1986), was developed for use in the Inland Empire area of Idaho and Montana. Extensive testing and refinement of PROGNOSIS, and subsequent development of variants throughout the West, lend credibility to the growth and yield projections of the model. WESSIN (Dixon 1988), a variant of PROGNOSIS, was specifically designed to model tree and stand growth and yield for mixed-conifers of the Westside Sierra Nevada in California. It should be noted, however, WESSIN was not designed to model the effects of air pollutants on tree and stand growth.

The phytotoxic effects of ozone exposure on conifers are a characteristic chlorotic mottle, increased membrane permeability, premature leaf senescence and decreased photosynthetic capacity (Sharpe and Sheld 1986; Miller and Evans 1974; Reich and Amundson 1985). The greatest injury is generally in the older needles and the lower crown. Foliar injury has been found at 24 hour concentrations of 50-60 parts per billion (Miller et al. 1982).

Needle foliage is represented in WESSIN by a live crown ratio variable (the ratio of live crown length to total tree height expressed as a percent, hereafter referred to as crown ratio). Crown ratio is an independent variable in WESSIN diameter and height growth equations. The crown ratio model assumes a full cohort of needles, which for ponderosa pine generally consists of 5 age classes. Because ozone causes premature needle senescence, generally in the lower crown, the effect is hypothesized as a reduced crown ratio. This assumption implies a loss of foliage from the bottom of the tree only and is a simplification of ozone damage. Leaf area index or other crown variables would be preferable to model premature needle senescence. Live crown ratio, however, is the only crown variable in WESSIN.

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²NSI Technology Services, U.S. EPA Environmental Research Laboratory, 200 SW 35th Street, Corvallis, OR 97333

METHODS

Diameter and height growth in WESSIN are modelled as semi-empirical exponential equations. Diameter and height growth sensitivities to the crown ratio variable may be evaluated by inspection of growth equation forms and crown ratio coefficient signs. Model sensitivity is defined here as the difference in projections of diameter at breast height (dbh), dbh growth, height, height growth, total volume and number of trees for manipulated crown ratio levels. Crown ratio scenarios can be developed and rationalized, but model sensitivity may also be tested by using crown ratio extremes.

A projection of four 10-year cycles may be appropriate. Cycle length should be based on 10-year height and radial increment data used to calibrate the model (Dolph 1988a,b). A 40-year projection period is considered an appropriate span to track model sensitivity to crown ratio changes. Five scenarios are being considered to simulate changes in crown ratio levels. The control scenario allows the model to cycle using the crown ratio prediction equation in WESSIN. If crown ratios are recorded in the field, they can be used as the initial values. The other four crown ratio scenarios follow. Crown ratios can be: (1) fixed at 95% over the cycles; (2) initially predicted by the model and then reduced by 20% at the beginning of each cycle; (3) initially predicted by the model and then reduced by 20%, 25%, 33% and 50% for cycles 1-4, respectively; and (4) fixed at 0% over the cycles. All species can be projected, but only the crown ratio of ponderosa pine trees could be altered.

The scenarios hypothesize "normal" growth by the control, two levels of reduced crown ratios and the extremes of near full and no live crown. The first reduced crown ratio scenario can be rationalized by assuming that ozone causes the premature senescence of the oldest age class of needles in the first cycle, the second oldest age class of needles in the second cycle and so on until all that remain after the fourth cycle are the current year needles. Because healthy ponderosa pine trees normally have 5 age classes of needles, this represents an approximate 20% per cycle decrease from what should have been present. For example, assuming an initial crown ratio of 50%, this scenario would result in 40%, 32%, 25.6% and 20.5% crown ratio for cycles 1-4, respectively. This reflects a decreasing reduction in crown ratio for each subsequent needle age class that dies.

Assuming the loss of an age class of needles per cycle, the second reduced crown ratio scenario decreases the crown ratio as a percent of the remaining age classes of needles in that cycle (by the last cycle, there are only two age classes of needles remaining, so the loss of the oldest age class results in a 50% reduction in live crown). The 95% crown ratio scenario can be considered as an upper bound reference and 0% crown ratio can be considered as a lower bound reference for dbh and height growth. The projections represent the full range of dbh, height, volume and mortality sensitivity to the crown ratio variable for a given dataset and stand conditions.

Figure 1 shows mean ponderosa pine tree crown ratio plotted by cycle for the five scenarios. From top to bottom: (1) crown ratio values were fixed at 95%, (2) control, (3) decrease predicted crown ratio values by 20% per cycle, (4) decrease predicted crown ratio values by 20%, 25%, 33%, and 50% per cycle and (5) crown ratio values fixed at 0%. Note the crown ratio scenario labelled control (model calculated) as compared to the four alternative scenarios.

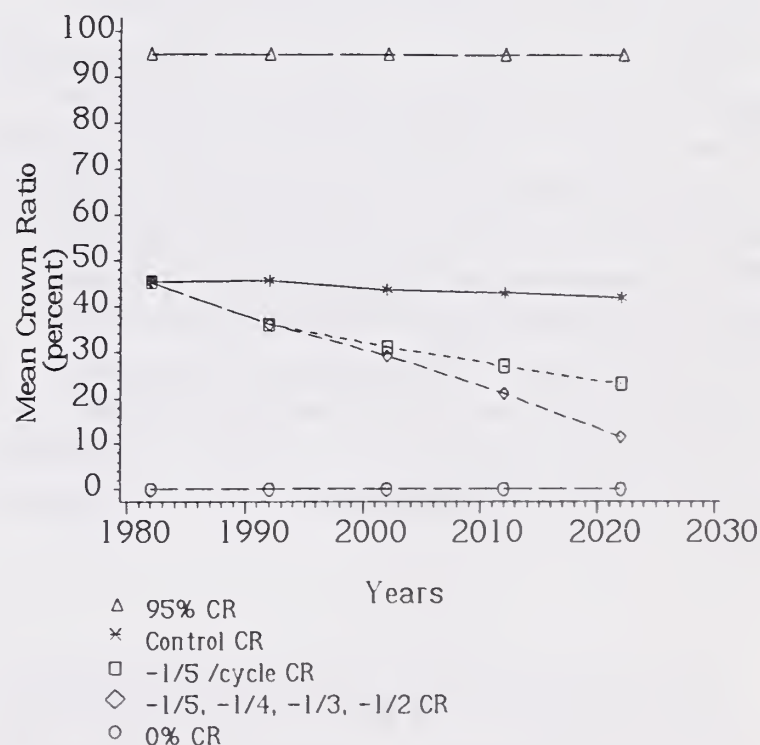


Figure 1. Mean ponderosa pine tree crown ratio plotted by cycle for the five scenarios.

EQUATION ANALYSIS EXAMPLE

Large tree diameter growth is modelled in WESSIN as a log-linear regression. Separate equations are used

depending on the availability of site index information. When assuming site index information is available, the following equation is the log-linear model for change in diameter growth squared.

$$\begin{aligned} \text{Ln}(dds) = & \text{LOC} + c_1 * \text{ELEV} + c_2 * \text{SL} + \\ & c_3 * \text{SL}^2 + c_4 * \text{SITE} + b_1 * \text{Ln}(\text{DBH}) \\ & + b_2 * \text{DBH}^2/1000 + b_3 * \text{CR} + b_4 * \\ & \text{PBAL}/(\text{Ln}(\text{DBH} + 1)/100) + b_5 * \text{Ln}(\text{PBA}) \end{aligned}$$

where:

DBH = diameter at breast height
 CR = $(\text{lcr} * \text{lcr}) / \text{Ln}(\text{DBH} + 1)/1000$
 lcr = live crown ratio expressed
 as percent (0-99)
 PBAL = basal area in larger trees on a given point
 PBA = total basal area on a given point
 LOC = location constant dependent on latitude
 ELEV = average stand elevation in hundreds of feet
 SL = average stand slope expressed as a percent
 SITE = 50-year site index at breast height age

The dependent variable is the natural log of the change in inside bark diameter growth squared. Crown ratio appears as an additive independent variable multiplied by a positive coefficient. As crown ratio values decrease, the natural log of the change in diameter growth squared decreases. Because crown ratio is an untransformed variable in the equation, it can be zero without forcing diameter growth to zero. As crown ratio approaches zero, diameter growth decreases and death occurs in the field. However, even at very low crown ratios, diameter growth is often measurable. The equation is not conditioned to go to zero as crown ratio goes to zero and thus cannot reflect tree death at very low and zero crown ratio. All growth and mortality equations should be analyzed relative to the asymptotic properties and contribution of crown ratio.

DISCUSSION AND RECOMMENDATIONS

Empirical and semi-empirical growth equations can only be used within the bounds of the data from which they were developed. Leary (1988) states, "Analysis has been constrained by what could be done with available data, not what needed to be done. In addition to having too much data, one could argue that much of the data was for the wrong conditions - too much in the middle range of predictor variables, and not enough at the boundaries".

Simply presenting the mean and range of a predictor

variable is not enough. A calibration data table may imply, via the range of a predictor variable, that a wide range of data were part of the calibration dataset. If no or few extreme observations exist, the model will not behave properly at the extremes and cannot be applied outside the narrow range where the majority of the data exist. User's guides should be explicit in stating appropriate conditions for model use. Model users are the final arbiters. However, they must be given adequate guidelines to decide whether a model is appropriate for their particular research.

Some models can be conditioned to behave in the extremes or regions where no data exist. Often, several alternative models perform adequately. In many empirical applications, choosing a sigmoid model that has an appropriate inflection point and asymptote is important. Such a model is less vulnerable to aberrations or gaps in calibration data. Bunge (1967) stated, "Those modelling at lower (more aggregate) resolution levels would do well to select equations having a theoretical basis and having interpretable numerical constants, as well as goodness of fit".

Looking at the dbh growth equation, crown ratio could go to zero without forcing the natural log of diameter growth squared to zero. A naive solution might be to substitute the natural log transformation of crown ratio in equation (1) for the crown ratio predictor variable. By exponentiating both sides of the equation, the effect of the natural log transformation of the crown ratio variable is apparent. If crown ratio went to zero, the change in diameter growth squared would go to zero. The nonlinear equation would need to be fit directly, however, for the equation to exhibit this property.

Substituting natural log of crown ratio for crown ratio and exponentiating the equation is only a first step. All coefficients would need to be re-estimated by nonlinear least squares with the original calibration data. In fact, depending on how the equation was developed, new predictor variables or different transformations of existing predictor variables may be significant. Also, the crown ratio dataset needs to be supplemented with adequate samples near the extremes. Choosing equations with a theoretical and biological basis is important. Although it is possible for changes to be implemented, satisfactory results may be elusive. An empirical model sensitive to changes in crown ratio is still just an empirical model.

LITERATURE CITED

- Bunge, M. 1967. Scientific research I: The search for system. Springer Verlag. New York. 536 p.
- Dixon, G. E. 1988. The western Sierra Nevada PROGNOSIS variant (WESSIN). USDA For. Serv. WO Timber Management, Fort Collins, CO. 76p.
- Dolph, K. L. 1988a. Prediction of periodic basal area increment for young-growth mixed conifers in the Sierra Nevada. USDA For. Serv. Res. Pap. PSW-190. 20 p.
- Dolph, K. L. 1988b. Predicting height increment of young-growth mixed conifers in the Sierra Nevada. USDA For. Serv. Res. Pap. PSW-191. 7 p.
- Leary, R. A. 1988. Some factors that will affect the next generation of forest growth models. In: Alan R. Ek, Stephen R. Shifley and Thomas E. Burk, eds. Proceedings of IUFRO Forest Growth Modelling and Prediction Conference, August 24-27, 1987. Minneapolis, Minnesota. USda For. Serv. Gen. Tech. Rep. NC-120. pp. 22-32.
- Miller, P. R., Taylor, O. C. and R. G. Wilhour. 1982. Oxidant air pollution effects on a Western coniferous forest ecosystem. EPA-600/D-82-276, Environmental Research Laboratory, Corvallis, OR 97333
- Miller, P. R. and L. S. Evans. 1974. Histopathology of oxidant injury and winter fleck injury on needles of Western pine. *Phytopathology* 64:801-806.
- Riech, P. B. and R. G. Amundson. 1985. Ambient levels of ozone reduce net photosynthesis in tree and crop species. *Science* 230:566-570.
- Sharpe, P. J. H. and H. W. Sheld. 1986. Role of mechanistic modeling in estimating long-term pollution effects upon natural and man-influenced forest ecosystems. p.76-82. In: Proceedings of workshop on controlled exposure techniques and evaluation of tree responses to airborne chemicals. NCASI Tech. Bull. No. 500. 82p.
- Stage, A. R. 1973. Prognosis model for stand development. USDA For. Serv. Res. Pap. INT-137. 32p.
- Wykoff, W. R. 1986. Supplement to the user's guide for the stand Prognosis model version 5.0. USDA For. Serv. Gen. Tech. Rep. INT-208. 36p.

Damage and Control of Diseases of Southwest Ponderosa Pine¹

Frank G. Hawksworth, Charles G. Shaw III, and Borys Tkacz²

Abstract.--Ponderosa pine is affected by an array of tree diseases in the Southwest. The most serious of these are dwarf mistletoes, root diseases, trunk decays, limb rust, needlecasts, and abiotic disorders (drought and winter drying). Research is ongoing to quantify the effects of diseases on various resource values including timber, recreation, scenic beauty, wildlife habitat, biodiversity, and water yields.

Diseases of ponderosa pine (*Pinus ponderosa* Laws. subsp. *scopulorum* E. Murray) have long been recognized as serious factors affecting forest productivity in the Southwest. Disease research was initiated concurrently with silvicultural studies on southwestern ponderosa pine. With the signing of a Memorandum of Understanding between the USDA Division of Forest Pathology and District III (now Region 3) of the Forest Service in 1910, a long period of forest pathology research on ponderosa pine began at the Fort Valley Experimental Forest and elsewhere in the Southwestern Region.

The major diseases of ponderosa pine throughout its vast range in western North America are discussed by Hawksworth and Shaw (1988). Lightle (1967) and Walters (1978a) describe diseases of ponderosa pine in the Southwest. In this discussion, we emphasize diseases that are currently of concern to forest managers in the Southwest.

Tree diseases seriously affect ponderosa pine forests managed for either timber production or recreation. Diseases discussed here include dwarf mistletoes, root diseases, rusts, trunk decays, needle and twig blights, and abiotic disorders. Diseases specific to nursery crops or natural seedlings are not included; readers are referred to a new handbook on nursery pests (USDA 1989) for this information.

1

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2

Frank G. Hawksworth and Charles G. Shaw, III, Plant Pathologists, USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO and Borys M. Tkacz, Plant Pathologist, USDA Forest Service, Forest Pest Management, Flagstaff, AZ.

Even though diseases probably cause more damage to southwestern ponderosa pine than insects and fire combined, there are few quantitative data on losses. In addition to timber and recreation losses, diseases impact other resources such as wildlife habitat and scenic beauty. Data on these effects are also lacking, but the need for such information is increasing as foresters implement integrated resource management.

DWARF MISTLETOES

Southwestern dwarf mistletoe (*Arceuthobium vaginatum* (Wild.) Presl subsp. *cryptopodum* (Engelm.) Hawksw. & Wiens) is by far the most widespread and damaging disease agent of southwestern ponderosa pine (Korstian and Long 1922, Andrews and Daniels 1960, Hawksworth 1961, Hawksworth and Wiens 1972). The mistletoe occurs essentially throughout the range of ponderosa pine in Arizona and New Mexico, and also ranges north to Colorado and southern Utah; east to West Texas; and south to Sonora, Chihuahua, and Coahuila, Mexico. Southwestern dwarf mistletoe is also common on Arizona pine (*Pinus ponderosa* var. *arizonica* Engelm. = *P. arizonica* Engelm.) and Apache pine (*P. engelmannii* Carr.) in southern Arizona and New Mexico. In northern New Mexico, Rocky Mountain bristlecone pine (*P. aristata* Engelm.) is occasionally infected when growing near infected ponderosa pines. Other associated conifers are not parasitized by this dwarf mistletoe but they are hosts of other species of *Arceuthobium*. Nearly 40% of the commercial ponderosa pine type throughout the Southwest is affected by dwarf mistletoe (H. Maffei, personal communication), but infection is much higher in some areas, for example 70 percent on the Lincoln National Forest in southern New Mexico (Hessburg and Beatty 1986). Annual losses in ponderosa pine due to dwarf mistletoe in the Southwest are estimated at 20 million cubic feet (H. Maffei, personal communication).

Dwarf Mistletoe Effects

Dwarf mistletoe affects ponderosa pine forests in many ways:

They Reduce Growth

Dwarf mistletoes affect diameter, height, and volume growth. They typically do not affect height or radial growth until they invade the upper half of the crown. Disease intensity in trees is commonly assessed using the 6-class dwarf mistletoe rating (DMR)³ system (Hawksworth (1977)). In this system a tree with infection confined to the lower half of the crown would be Class 3. Growth is reduced markedly as the level of infection increases in the upper crown. For example, the last 5 years' radial growth of ponderosa pine in New Mexico was reduced 9% for DMR Class 4 trees, 23% for Class 5, and 53% for Class 6 (Hawksworth 1961). As a rule, a given mistletoe rating reduces height growth more than diameter growth.

They Increase Mortality Rates

Infection by ponderosa pine dwarf mistletoe, especially when severe, accelerates tree mortality (Korstian and Long 1922, Hawksworth 1961, Maffei 1989). Most ponderosa pines that are killed by dwarf mistletoe have a DMR of 6. Mortality in ponderosa pine stands in southern New Mexico was about 3% over 10 years for trees with a DMR of 3 or less, 9% for Class 4 trees, 12% for Class 5 trees, and 38% for Class 6 trees (Hawksworth and Lusher 1956).

In a more detailed study followed for over 30 years at Grand Canyon, Arizona, mortality was found to be related to mistletoe infection severity and tree size (Hawksworth and Geils 1990). Class 6 trees under 9 inches d.b.h. lived for an average of only 7 years while those over 9 inches lived for an average of 10 years. Comparable figures for trees in DMR Classes 4 or 5 were 17 years for small trees and 25 years for large trees. At Grand Canyon, Arizona, mistletoe-infected ponderosa pines were more readily killed by fire than uninfected trees (Harrington and Hawksworth 1989).

They Decrease Seed Production

Although quantitative data are limited,

³ For the DMR rating system, the live crown of a tree is visually divided into thirds and each third rated for mistletoe intensity as (0) for no visible mistletoe shoots or witches' brooms, (1) for light infection (less than half of the branches infected), or (2) for heavy infection (more than half of the branches infected). The ratings for each third are then added to obtain a tree rating, which ranges from "0" for a healthy tree to "6" for a tree heavily infected in each third. Ratings of all live trees (including uninfected trees) can be averaged to obtain a stand or plot rating.

ponderosa pine dwarf mistletoe reduces cone and seed production. Korstian and Long (1922) found that the "reproductive value" (yield of seed per pound X number of seeds per pound X germination percent) of severely infected ponderosa pines in Arizona was about 75% less than that of comparable, uninfected trees. Myers (1974) recommends that ponderosa pines with a DMR of 4 or higher should not be left as seed trees.

They Reduce Wood Quality

Wood anatomy within dwarf mistletoe stem infections is markedly altered. No detailed studies have been conducted on ponderosa pine, but we may assume from studies on lodgepole pine that mistletoe-affected wood has tracheids that are shorter and distorted, with more ray tissues and consequently reduced strength (Pirto et al. 1974). The importance of this strength reduction is presumably slight since most of the affected wood is near the outside of the log and is removed in milling. Increased knot size and bole distortions caused by persistent brooms and trunk infections are probably more serious, but these effects have not been quantified.

They Predispose Trees to Attack by Insects

Ponderosa pines heavily infected with dwarf mistletoe are frequently attacked and killed by secondary bark beetles, primarily *Ips*. spp. (Parker 1979; Stevens and Hawksworth 1970, 1984). There have been few studies on interrelationships between dwarf mistletoe and *Dendroctonus* beetles in the Southwest, but mortality caused by *D. adjunctus* in southern New Mexico is directly related to the severity of dwarf mistletoe infection (Parker et al. 1975, Stevens and Flake 1974). Wagner and Mathiasen (1985) studied a pandora moth (*Colorada pandora*) outbreak on the North Kaibab Plateau and found that, while all trees were defoliated, mortality was concentrated in pines that were severely infected by dwarf mistletoe.

They Have Many Ecological Effects

Dwarf mistletoes influence several ecological relationships in ponderosa pine forests (Linhart 1988), including the rate and direction of stand succession. For example, some ponderosa pine stands in the Southwest are being replaced by Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) because overstory pines are killed by dwarf mistletoe and immune Douglas-firs in the understory are released. When dwarf mistletoe kills groups of ponderosa pines, understory vegetation and microclimate in the openings created are markedly affected. The increased "edges" created by such openings may enhance the wildlife habitat value to some birds and small mammals.

Dwarf Mistletoe Control

Dwarf mistletoes can be effectively and economically controlled by cultural means (Beatty 1982b, Hawksworth and Shaw 1984, Johnson

and Hawksworth 1985, Scharpf and Parmeter 1978, Wicker and Hawksworth 1988), particularly even-aged cutting methods. Mistletoes are amenable to cultural treatments because:

- (1) They are obligate parasites; that is, they require a living host to survive. Once an infected tree or branch is cut it is no longer a threat.
- (2) They are generally host specific and usually attack one host or a group of closely related species. Resistant species can frequently be favored to minimize losses.
- (3) They have long life cycles, i.e., the time from infection to seed production is 5-6 years, or longer. Long life cycles slow population build-up.
- (4) They have a slow rate of spread. Seed dispersal distances are usually less than 50 feet from the tops of overstory trees and 20-30 feet from smaller trees. Added to its long life cycle, this limits rate of spread of dwarf mistletoe through even-aged stands to about 1-2 feet per year.
- (5) They cause obvious damage. Damage due to dwarf mistletoe is readily apparent because of mistletoe plants, witches brooms, and declining or dead trees. Infested portions of stands can be readily delineated.

Various silvicultural treatments can reduce or eliminate damage caused by dwarf mistletoes. Clearcutting is the easiest to implement and more surely breaks the disease cycle between old and new stands. Where planting success is poor or unpredictable, shelterwood or seed tree methods may be preferable. However, shelterwood or seed tree cuttings will succeed only if infected seed trees are removed before they can infect the new, young stand. Infected seed trees should be cut before the young stand is about 3 feet high or, depending on site factors, about 10 years old. Small trees present little target area and thus intercept few mistletoe seeds (Wicker and Shaw 1967).

Silvicultural options are limited in mature, heavily infested stands where replacement is usually recommended. In diseased stands younger than harvest age, thinning will improve growth if infection severity is light and residual trees are not too heavily infected (Hawksworth 1978). The 6-class DMR system can also be used to quantify mistletoe severity in stands by calculating, from a representative sample, the mean DMR for all live trees, including non-infected ones. As a rule, stands with an average DMR over 3 should not be thinned (Hawksworth 1978). Usually the most severely infected trees (DMR Class 4-6) should be removed, even though they are frequently the largest, because their growth response will be limited, and dwarf mistletoe will intensify rapidly in them. The DMR system may also be utilized to help set cutting priorities, with

the most heavily infested stands receiving early harvest entries.

Additional control techniques may be applicable in recreational or residential areas because of the high value of individual trees. These include pruning of branches and witches brooms, fertilization and supplemental watering, and also planting of non-susceptible species (Lightle and Hawksworth 1973; Scharpf et al. 1987, 1988). Beatty (1982a) gives practical guides for minimizing dwarf mistletoe damage and hazards in summer home sites in Arizona.

Recently, the growth regulator Ethephon (an ethylene-releasing agent) has been approved by the Environmental Protection Agency for limiting spread of dwarf mistletoes (Nicholls et al. 1987). Tests on ponderosa pine dwarf mistletoe at Los Alamos, New Mexico show it to be an effective therapeutant (Beatty et al. 1989). Ethephon does not affect the mistletoe's endophytic system within the host, but by causing the aerial shoots to fall off, it temporarily limits seed dispersal. Shoots will resprout from the established root system after 2 to 4 years, and re-application is necessary to prevent seed production. The chemical may be useful in high-value stands, such as in recreation areas, to protect understory trees from dwarf mistletoe.

Effects of dwarf mistletoe have been incorporated into the growth and yield model RMYLD for even-aged and two-storied stands of ponderosa pine in the Southwest and Central Rocky Mountains (Beatty 1982b, Edminster 1978, Walters 1978b). Models are being developed for uneven-aged ponderosa pine stands and for mixed conifer stands that include ponderosa pine (Edminster et al. 1990, Edminster and Hawksworth 1984, Maffei 1989).

ROOT DISEASES

Root diseases affect ponderosa pine in many parts of the West where annual losses from these diseases are estimated at 240 million cubic feet per year (Smith 1984). Even though breakdowns of this loss by tree species are not available, ponderosa pine likely contributes less to this figure than Douglas-fir and true firs because it is less often damaged by root diseases (Hagle and Goheen 1988). There is relatively little information on the root diseases of Southwestern ponderosa pine, and until recently they were thought to be of minor importance.

In the Southwest, *Armillaria* root disease, caused by one or more species of *Armillaria*, including *A. ostoyae* (Romagn.) Herink, (Wargo and Shaw 1985), is not uncommon throughout the ponderosa pine type, but damage is generally light (Wood 1983). A notable exception is in the Jemez Mountains of northern New Mexico, where *Armillaria* root disease causes extensive mortality in certain plantations (Weiss and Riffle 1971) and in one large natural forest that has been periodically logged by selective

cutting for over 50 years (Wood 1982). In this area, as commonly happens with root diseases, prior management activities seem to have exacerbated the problem.

Annosus root disease caused by *Heterobasidion* (*Fomes*) *annosum* (Fr.) Bref. also occurs on ponderosa pine in the Region (Mielke and Davidson 1947), but damage is again slight (Wood 1983). Black stain root disease, caused by *Ophiostoma* (*Leptographium*) *wagneri* (Goheen & Cobb) Harrington, has been confirmed on Douglas-fir and pinyon (*Pinus edulis* Engelm.) in the Southwest (Harrington and Cobb 1986); however, *L. wagneri* has not been confirmed on ponderosa pine (T. Harrington personal communication, 1989). Below are some brief descriptions of each of these diseases.

Armillaria Root Disease

Taxonomic and genetic research has identified several biological species and clones of *Armillaria*, but their relative pathogenicity and host specificity are poorly understood (Wargo and Shaw 1985). The fungus is easily recognized by the white mycelial fans and fungal, root-like structures called rhizomorphs found on dead and dying trees (Hadfield et al. 1986, Morrison 1981, Williams et al. 1986). Mortality may be localized, or extensive in ponderosa pine stands such as those in south-central Washington (Shaw et al. 1976, Shaw and Roth 1976) and northern New Mexico (Weiss and Riffle 1971, Wood 1982).

Mortality from *Armillaria* and other root diseases in ponderosa pine often is aggregated in disease centers, which enlarge over time (Wargo and Shaw 1985). *Armillaria* disease centers may spread outward by fungal transfer from tree to tree at a rate of up to 3 feet per year and survive for centuries (Adams 1974, Shaw and Roth 1976). This condition effectively puts portions of affected stands "out of production" for a rotation or longer because the fungus survives in the roots of infected trees and continually reinfects newly established regeneration (Shaw 1980). Logging often increases problems from this disease because roots on remaining stumps quickly become colonized, which increases the site's inoculum load (Shaw 1980). A recent study in Oregon (Filip et al. 1989) suggests, however, that normal precommercial thinning operations in ponderosa pine affected by *Armillaria* root disease will not increase damage from the disease.

Some general strategies for control of *Armillaria* root disease in ponderosa pine appear to be effective in at least one locale (Roth et al. 1977, 1980; Roth and Rolph 1978). One control strategy uses special marking guidelines for thinning and partial-cut harvest operations that call for "push-felling" and stump removal of all trees within a barrier of prescribed width around known infected trees. Another strategy calls for the removal of root systems of infected trees during harvest (Russell 1978).

These procedures remove inoculum from the soil, reduce the likelihood of new infections on individual trees, and limit spread of disease centers into healthy portions of the stand. Unfortunately, stump removal is expensive and its use is limited to certain soil types on rather gentle terrain. It is therefore necessary to determine the relative benefits that might accrue from root removal operations or implementing other control strategies. An experimental control operation by inoculum removal is scheduled for implementation next spring in the severely infested stands in the Jemez Mountains (Shaw, unpublished).

Knowledge of species susceptibility to *Armillaria* root disease is important to management. Over most of its range, ponderosa pine is less damaged by *Armillaria* root disease than are true firs or Douglas-fir (Morrison 1981). Foresters can utilize this differential susceptibility to reduce damage by favoring ponderosa pine in areas affected by *Armillaria* root disease. Such actions require caution and site specific information, however, because in certain areas (i.e. south-central Washington and northern New Mexico) ponderosa pine appears to be more susceptible to *Armillaria* root disease than Douglas-fir. Studies to evaluate the relative susceptibility of tree species native to the Jemez Mountains, where this disease is troublesome, are in progress (Wager and Shaw, unpublished).

Past trials on chemical control of *Armillaria* root disease in ponderosa pine have met with little success (Filip and Roth 1977, 1987). In contrast to annosus root disease, spores are of little significance to local disease development. Thus treatment of stumps to prevent surface infection by spores is impractical.

Annosus Root Disease

Annosus root disease, caused by *H. annosum*, occurs throughout the range of ponderosa pine. Root disease centers associated with pine stumps are reported from California, the Pacific Northwest, and the Northern Rockies; however, damage in Southwestern ponderosa pine is primarily seen as seedling mortality around infected stumps (Hawksworth, unpublished). In contrast, the fungus is not uncommon on large white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.) in the Southwest (R. Gilbertson, personal communication). Detection of annosus root disease can be difficult unless the characteristic sporophores are present, or one is familiar with the white, spongy pocket rot and laminated decay (Bega 1978, Hadfield et al. 1986).

Like *Armillaria*, annosus root disease can kill trees in enlarging disease centers; however, unlike *Armillaria* root disease, spores of *H. annosum* are involved in disease spread and intensification. These spores are released from sporophores and carried by wind throughout the forest. Spores landing on freshly cut stump

surfaces germinate and produce fungal mycelia that grow down through stump wood and into lateral roots. Infections can develop on adjacent, live trees if healthy roots contact colonized stump roots--a process that may eventually lead to tree death and development of new disease centers (Hadfield et al. 1986). For this reason, treatment of pine stumps with borax to prevent surface infection by spores, and thus reduce the number of new infections that develop after logging (Graham 1971), is becoming a routine procedure in California, Oregon, and Washington. The utility of this control depends on the effectiveness of the borax treatment and the proportion of trees and stumps in the stand that were infected prior to logging. Local forest pathologists should be consulted if H. annosum is present at high levels in stands planned for silvicultural treatment. As with other root diseases, there is an increased concern with annosus root disease in recreation areas (Felix et al. 1974).

Current research on H. annosum suggests the existence of different host-specific variants or biotypes (Chase et al. 1989, Worrall et al. 1983). This host specificity provides an opportunity for disease control through planting trees resistant to the primary biotype present within an area. For example, a recent study in California (Kliejunas 1986) indicated that ponderosa pine seedlings could be planted with little risk from root disease around true fir stumps infected with H. annosum. Since H. annosum occurs on white fir and ponderosa pine in the Southwest (Mielke and Davidson 1947), knowledge of such host specificity may become useful to managers.

Black Stain Root Disease

Black stain root disease, caused by Ophiostoma (Leptographium) wagneri, occurs in scattered areas of ponderosa pine in California, the Pacific Northwest, and the Northern Rockies. This disease has not been confirmed on ponderosa pine from any location in the Southwest, even though isolates of Leptographium sp. pathogenic to ponderosa pine seedlings have been reported (Livingston et al. 1983). Although this disease was first described on ponderosa pine and pinyons (Wagner and Mielke 1961) and can be locally severe, it is of little consequence to management of either species in the Southwest. Black stain root disease also occurs on Douglas-fir in the Southwest, but is again of little concern (Harrington and Cobb 1986, 1988).

In ponderosa pine, black stain root disease causes symptoms similar to those caused by other root pathogens, including reductions in terminal and radial growth, needle chlorosis, and crown thinning (Hadfield et al. 1986). Black stain can be distinguished from other root diseases by the dark-brown to purple-black discoloration in the sapwood of the lower bole and root collar (Hadfield et al. 1986). The fungus grows in sapwood and plugs tracheids, which prevents

water transport. Black stain root disease is a wilt disease that usually causes rapid tree decline and death (Hessburg and Hansen 1987). Unlike root diseases caused by Armillaria sp. and H. annosum, black stain root disease does not cause wood decay.

Leptographium wagneri can be vectored over long distances by root-feeding bark beetles and weevils. Hylastes macer has been identified as a putative vector of the disease on ponderosa pine (Harrington and Cobb 1988). New infections usually are initiated in low-vigor hosts since these beetles prefer, or are more successful at attacking, weakened hosts. Once the pathogen is established, however, it infects adjacent trees, irrespective of their vigor, via root grafts or by growing a short distance through soil (Goheen 1976, Hessburg and Hansen 1986, Hicks et al. 1980). The disease spreads at a rate of about 3 feet per year in ponderosa pine infection centers (Cobb et al. 1982).

Unlike Armillaria spp. and H. annosum, L. wagneri dies with its host. To survive and continue to spread to new hosts, the fungus requires a continuous network of living host roots. Where black stain root disease is a problem in ponderosa pine, control strategies have involved cutting all pine in a 50-foot buffer around infection centers and favoring alternate species in these areas (Hadfield et al. 1986). This technique is used because, like H. annosum, there are known variants of L. wagneri that exhibit a considerable degree of host specificity (Harrington and Cobb 1984, 1988). Interestingly, L. wagneri, Armillaria sp., and H. annosum can all occur in the same pine root systems (Filip and Goheen 1982).

Modeling Root Disease Behavior

To provide forest managers with a means to evaluate impacts of root disease in affected stands, and to project the effects of silvicultural operations on disease levels and stand production, a root disease model was developed for western coniferous forests (Shaw et al. 1985, Eav and Shaw 1987, Stage et al. 1989). At present, this model does not have functions for annosus or black stain root disease, although interest has been expressed in incorporating them (Shaw et al. 1989).

The model can, however, be used to predict effects of pathogenic Armillaria in stands of ponderosa pine or other conifers under various management regimes (Hawksworth and Shaw 1988). A keyword system allows users to input root disease inventory data, remove stumps, modify pathogen behavior, thin, and activate windthrow or bark beetle attacks. The model is attached to several variants of the Stand Prognosis growth and yield model (Wykoff et al. 1982). Through modification of the GENGYM growth and yield model (Edminster et al. 1990), it should be available soon for general use in the Southwest. The root disease model can be accessed via the Data General Growth and Yield

Submittal System of the USDA Forest Service (Sleavin 1989) by selecting the keyword "PEST" (Gladden 1989) from the Keyword Main Entry Menu.

A key element of the western root disease model is its ability to simulate interactions between root diseases and bark beetles. This feature is particularly important as root diseases rarely operate independent of other factors within a stand, particularly bark beetles. For example, in his survey of National Forests in the Southwest, Wood (1983) reported losses from root diseases as occurring in combination with either bark beetles or dwarf mistletoe or both. Livingston et al. (1983) also document interactions between root diseases and bark beetles in the Southwest.

The example of output from this model given by Hawksworth and Shaw (1988) for simulated plantings on a site with severe *Armillaria* root disease shows that ponderosa pine suffers less damage than Douglas-fir. The relative susceptibilities of these species can be changed in the model if local knowledge suggests they should. Research is in progress to clarify geographic and site hazard differences in species susceptibility to infection by and damage from *Armillaria* root disease.

STEM RUSTS

Limb rust is the most widespread stem rust of ponderosa pine in the Southwest (Mielke 1952, Peterson 1967). Two species of the rust occur in the Southwest. *Cronartium arizonicum* Cummins (Cummins 1984), which requires an alternate host (*Castilleja* spp.) to complete its life cycle, and occurs throughout most of the Southwest. The other, referred to in the literature as *Peridermium filamentosum* Pk., spreads directly from pine to pine. It occurs in northern Arizona and probably in northern New Mexico (Peterson 1967, 1968). Effects of the two limb rust species on ponderosa pine are similar: they cause no branch swellings but progressively kill branches as the fungus spreads systemically up and down the crown in the xylem of the bole and branches. When crowns have been seriously reduced by disease, trees die, usually through attack by secondary bark beetles. Baker et al. (1987) studied the disease in southern Utah and developed a system to rate severity of limb rust so that crown loss and mortality could be predicted. This system is being evaluated to quantify rust impact on the scenic beauty of affected trees and forests (Baker and Rabin 1988).

Western gall rust caused by *Peridermium harknessii* J. P. Moore (= *Endocronartium harknessii* (J. P. Moore) Y. Hiratsuka) is a widespread stem rust of hard pines in the western North America, but it only occurs in a few locations in the Southwest (Peterson 1967). The rust spreads directly from pine to pine without an alternate host (Peterson 1960, Riffle and Peterson 1986). As with limb rust, western

gall rust has two forms, but these are distinguishable by gall morphology and aeciospore color (Mielke and Peterson 1967). Only the white-spored race has been confirmed on ponderosa pine in the Southwest. The orange-spored race was accidentally introduced into the Flagstaff area in the early 1950's on experimental planting stock from Placerville, California. Clipping off all visible galls prevented the rust from becoming established in native pine stands (Hawksworth, unpublished). Western gall rust can kill young pines, but it causes more loss through log degrade associated with stem swellings and distortion.

Comandra blister rust (*Cronartium comandrae* Pk.) is a serious pathogen of lodgepole pine and ponderosa pine in the Pacific Northwest and Interior Mountain West (Johnson 1986). It occurs rarely in the Southwest, having been found on ponderosa pine in Arizona (North Rim of Grand Canyon, Flagstaff, and near Prescott). The rust requires an alternate host, bastard toadflax (*Comandra umbellata* (L.) Nutt.), to complete its life cycle. The rust causes fusiform cankers on branches and trunks. Stem cankers ultimately girdle and kill the tree. Recently, severe outbreaks of the rust have been found on the introduced Eldarica pine (*Pinus eldarica* Medw.) at Prescott, Payson, and Sedona, Arizona (Gilbertson and Rosemeyer 1985). Curiously, the rust is rare on ponderosa pines growing near infected Eldarica pines. The rust causes so much damage to Eldarica pine that this tree should not be planted near populations of bastard toadflax.

From a management standpoint, the most important consideration for stem rusts is to assure that severely infected trees are removed during intermediate entries.

FOLIAGE DISEASES

Needle disease damage is often spectacular, but epidemics are typically cyclic and cause little mortality or growth loss in natural stands. Severe damage is usually associated with favorable climatic episodes or planting of trees that are of non-local sources.

Several needle casts of the family Hypodermataceae are common on ponderosa pine in the Southwest, including *Lophodermella cerina* (Darker) Darker, *Davisomycella ponderosae* (Staley) Dubin, and *D. medusa* (Darker) Darker (Darker 1932, 1967; Keener 1962; Staley 1967). *Lophodermella cerina* is by far the most damaging. It has caused severe reddening of more than 250,000 acres of ponderosa pine on the Coconino and Prescott National Forests, Arizona from 1955 to 1962 (Staley 1967, USDA Forest Service 1961). The fungus damaged nearly 20,000 acres of ponderosa pine on the Mescalero Apache Reservation and Lincoln National Forest in southern New Mexico in 1987 (Rogers and Maffei 1988) and an additional 1,450 acres on the Cibola National Forest, New Mexico, in 1988 (Rogers and Maffei 1989). This needlecast

causes acute reddening of the previous year's foliage which is cast prematurely. When epidemics last over several years, such as in the Arizona case, trees survive with only their current year's needles. Needlecast damage is most noticeable in stream bottoms and along edges of meadows, but the actual growth loss and mortality have not been quantified.

Elytroderma blight (Elytroderma deformans (Weir) Darker) is the most widespread and damaging needlecast of ponderosa pine in North America (Childs et al. 1971). The disease was reportedly at "epidemic" levels in Arizona and New Mexico in the 1930's (Lightle 1967), but now occurs only locally in the Southwest and causes insignificant damage. The fungus causes premature death of one-year-old needles and formation of witches' brooms that are often mistaken for those caused by dwarf mistletoe. A characteristic symptom of this disease is brown flecks in the cortex at the base on infected needles. The disease is most prevalent in low, moist areas, at edges of meadows, and on sides of steep canyons. When defoliation continues for several years, trees are killed, as has occurred at Lake Tahoe in California (Scharpf and Bega 1981).

CANKERS AND TWIG DISEASES

Ponderosa pine is attacked by relatively few canker diseases. Atropellis canker (caused by Atropellis piniphila (Weir) Lohman) is common on ponderosa pine in southern portions of New Mexico and Arizona (Lightle and Thompson, 1973). The elongated, diamond-shaped trunk cankers are distinguished by dark fruiting bodies of the fungus and the blue-black stain in the sapwood behind cankers. Cankers kill small trees, but most degrade and loss is associated with stem malformations and discolored wood.

Twig blight or Prescott scale is not caused by a forest pathogen but the syndrome was studied for so long by Southwestern forest pathologists that we include it here. Twig blight is characterized by small branch mortality in ponderosa pine. Even though trees of all sizes are affected, the blight is most common on saplings. Twig blight was first noticed in 1919, and was studied for more than 30 years before the causal agents were identified. The primary cause is a scale insect, Matsucoccus vexillorum Morrison, but it is usually found in association with secondary fungi (McKenzie et al. 1948). In the 1930's, twig blight was considered to be a new and seriously threatening disease of ponderosa pine. The threat of extensive damage led to large-scale eradication operations even before the causal agents were known. Thousands of affected trees were cut and destroyed in southwestern National Forests by CCC crews. Intensive surveys of the ponderosa pine forests throughout the West were conducted, but twig blight was found to be essentially restricted to Arizona and New Mexico. Although outbreaks have been sporadic and local since 1934, twig blight

incidence is currently increasing on the Chevelon Ranger District of the Apache-Sitgreaves National Forest and adjacent Fort Apache Indian Reservation in Arizona (Rogers and Maffei 1989).

DECAYS

Trunk rots cause serious volume loss in southwestern ponderosa pine, particularly in old-growth stands (Andrews 1955, Boyce 1961).

Red rot (also called red ray rot), caused by Dichomitus squalens (Karst.) Reid (= Polyporus anceps Pk.), is the major decay of living ponderosa pine in the Southwest (Andrews 1955, 1971; Long 1917). Andrews (1955) estimated that 15-25% of the gross volume in virgin stands in the Southwest is lost to red rot. The fungus commonly fruits on slash and sometimes on dead limbs of living ponderosa pine trees. Since bole infections emanate from infected dead branches over 1 inch in diameter with intact bark, branch pruning of the lower boles can reduce losses to red rot (Andrews 1955). Lightle and Andrews (1968) found that loss due to red rot in old-growth ponderosa pine on the Navajo Reservation in Arizona amounted to 15 % of the gross volume. The light selection harvesting system then used removed 48 % of the gross volume and reduced the volume loss to red rot to 9 % in the residual stand.

Red ring rot, caused by Phellinus (Fomes) pini (Thore.:Fr.) A. Ames, is the principal decay of ponderosa pine in Pacific Coast States and the Northern Rockies. It is rare on ponderosa pine in the Southwest, except for the Lincoln National Forest and adjacent Mescalero Apache Reservation in southern New Mexico (Lightle 1967). Even in these locations, red rot is more prevalent and damaging to old-growth ponderosa pine than is red ring rot.

Other decays of living ponderosa pine sometimes encountered in the Southwest are Fomitopsis officinalis (Vill.:Fr.) Bond. et Sing. (= Fomes laricis Jacq. ex Murr.), a brown cubical trunk rot; Phaeolus (Polyporus) schweinitzii (Fr.) Pat., a brown cubical butt rot usually associated with Douglas-fir; Veluticeps berkeleyi Cke., a dark brown cubical butt rot (Gilbertson et al. 1968); and Lentinus lepideus Fr., a brown cubical rot often associated with fire scars. Descriptions and keys to identification of these fungi and their decays are given by Gilbertson (1974), which describes more than 200 fungi that decay ponderosa pine in western North America.

ABIOTIC DISEASES

An array of environmental factors affect ponderosa pine throughout the West. These include climatic extremes, winter drying, top kill due to cold, frost damage to foliage, drought, salt toxicity, herbicide damage, hail damage, and air pollution (Miller 1978).

In the Southwest, periodic droughts are the primary abiotic factor affecting ponderosa pine. Several consecutive years of below normal rainfall in the 1950's led to the death of thousands of ponderosa pines in Arizona and New Mexico, usually in association with secondary bark beetles (Lightle 1967). Ironically, most mortality occurred just after the drought was broken and rainfall returned to near-normal levels and patterns. Plant-parasitic and mycorrhizal-parasitic nematodes were studied in ponderosa pines in drought-affected and non-drought stands in New Mexico, but results were inconclusive (Riffle 1967, 1968).

Lightning is a primary mortality factor in old ponderosa pine trees in many areas in the Southwest (Pearson 1950).

Winter drying, which is considered to be induced by drying winter winds when soil around the tree roots is still frozen, can cause spectacular damage to ponderosa pine and other southwestern conifers. Usually only the foliage is reddened and killed, but tree mortality may occur in severe cases. Winter drying affected about 150,000 acres of ponderosa pine and Douglas-fir in northern New Mexico in 1985, but most of the trees recovered (Owen 1986). Hail damage also can be severe in the Southwest: for example, on the Mescalero Apache Reservation in the late 1950's a severe hailstorm caused almost completely stripped ponderosa pine foliage on over 6,000 acres, and many trees were killed.

Ponderosa pine is quite susceptible to excess soil salinity (Spotts et al. 1972). Along roadsides where salt is used for deicing, needles frequently become discolored and trees die (Scharpf and Srago 1974, Walters 1977). Ponderosa pine is also seriously affected by air pollution in some areas, particularly by ozone in southern California (Miller 1978). Studies in Colorado suggest that Rocky Mountain ponderosa pine is more resistant to ozone injury than coastal ponderosa pine (Aitken et al. 1984). Little pollution damage to ponderosa pine in the Southwest has been detected to date. Surveys to evaluate sulfur dioxide damage to native forest vegetation in Arizona and New Mexico were conducted for several years by the Forest Insect and Disease Management branch of the Southwestern Region (Weiss 1974). Although unexplained needle flecking of ponderosa pine was found throughout the Southwest, this condition could not be attributed directly to sulfur dioxide emission sources, and no tree mortality resulted (Weiss 1974).

PEST COMPLEXES

The concept that a single forest pest acting alone kills trees is gradually being replaced by a realization that tree death typically results from complex interactions among pathological, entomological, and environmental factors. For example, *Armillaria* spp. often acts in association with other root diseases (Filip and

Goheen 1982), and bark beetles can be attracted to ponderosa pines infected by root pathogens (Cobb et al. 1974, Lessard et al. 1985) or dwarf mistletoe (Stevens and Hawksworth 1970, 1984). The pest combinations reported by Wood (1983) and Livingston et al. (1983) emphasize the importance of these interactions as causes of tree mortality in the Southwest.

Much of the marking for selective harvest of old-growth ponderosa pine in the Southwest was based on classification systems originally designed to identify trees at risk to attack by bark beetles (Thompson 1940, Schubert 1974). Research is currently underway to determine if these high-risk trees are so categorized because of pre-existing root disease conditions (Shaw, unpublished).

CONCLUSIONS

Diseases have seriously affected the health and productivity of Southwestern ponderosa pine forests for millennia. In 1910, the USDA Division of Forest Pathology, in cooperation with the US Forest Service, began investigating diseases of ponderosa pine in the Southwest, particularly dwarf mistletoe and red rot. Dwarf mistletoe (*Arceuthobium vaginatum* subsp. *cryptopodum*) affects nearly 40 percent of the ponderosa pine acreage in the Southwest and causes losses of more than 20 million cubic feet per year. Dwarf mistletoe, however, is amenable to silvicultural controls to minimize its effects in managed forests. Red rot (*Dichomitus squalens*) is the primary trunk rot of old growth ponderosa pine. Its importance is now limited because most old-growth stands have been entered.

Root diseases are serious in some cut-over stands of ponderosa pine. For example, *Armillaria ostoyae* is causing heavy mortality in northern New Mexico. *Heterobasidion annosum* causes some mortality in reproduction around infected stumps in southern New Mexico.

Limb rust (caused by two similar fungi, *Cronartium arizonicum* and *Peridermium filamentosum*), the only lethal rust disease of ponderosa pine in the Southwest, is more common in Arizona than in New Mexico. *Atropellis* canker (*Atropellis piniphila*) is common in some ponderosa pine stands in southern New Mexico, but damage is generally slight. Similarly, damage due to foliar diseases is generally minor, but can be spectacular, as in the 1950's epidemic of *Lophodermella cerina* that reddened ponderosa pine on over 250,000 acres in central Arizona.

Research on diseases of ponderosa pine is now concentrated on pest interactions. It is aimed at evaluating pest impacts on multi-resource values including timber, recreation, scenic beauty, wildlife habitat, biodiversity, and water yields.

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LITERATURE CITED

- Adams, D. H. 1974. Identification of clones of Armillaria in young-growth ponderosa pine. Northwest Science 48: 21-28.
- Aitken, W. M., W. R. Jacobi, and J. M. Staley. 1984. Ozone effects on seedlings of Rocky Mountain ponderosa pine. Plant Disease 68: 398-401.
- Andrews, S. R. 1955. Red rot of ponderosa pine. USDA Forest Service Agriculture Monograph 23, 34 p., Washington, D.C.
- Andrews, S. R. 1971. Red rot of ponderosa pine. USDA Forest Service Forest Pest Leaflet 123, 8 p., Washington, D.C.
- Andrews, S. R., and J. P. Daniels. 1960. A survey of dwarfmistletoes in Arizona and New Mexico. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Station Paper 49, 17 p.
- Baker, F. A., D. Rabin, W. Chengguo, and B. M. Tkacz. 1987. Rating the severity of limb rust in ponderosa pine stands. Proceedings of the 34th Western International Forest Disease Work Conference, p. 22-23.
- Baker, F. A., and D. Rabin. 1988. Using computer graphics to assess the visual impact of limb rust of ponderosa pine. Utah Science 49(4): 98-102.
- Beatty, J. S. 1982a. Biological evaluation. Hazard trees and dwarf mistletoe in six summer home areas, Payson Ranger District, Tonto National Forest, Arizona. USDA Forest Service, Southwestern Region, Forest Pest Management Report R-3 82-1, 37 p.
- Beatty, J. S. 1982b. Integrated pest management guide. Southwestern dwarf mistletoe, Arceuthobium vaginatum subsp. cryptopodum (Engelm.) Gill, in ponderosa pine. USDA Forest Service, Southwestern Region, Forest Pest Management Report R-3 82-13, 12 p.
- Beatty, J. S., H. Maffei, E. Collins, and M. Christian. 1989. Ethephon tests for ponderosa pine dwarf mistletoe in New Mexico. Proceedings of the 36th Western International Forest Disease Work Conference, p. 39-40.
- Bega, R. V., Tech. Coord. 1978. Diseases of Pacific Coast conifers. USDA Forest Service Agricultural Handbook 521, 206 p., Washington, D.C.
- Boyce, J. S. 1961. Forest Pathology, Third Edition, McGraw-Hill Book Co., New York, 572 p.
- Chase, T. E., et al. 1989. Genetics of intersterility in Heterobasidion annosum. P. 11-19 in: D. J. Morrison, ed. Proceedings 7th IUFRO Conference on Root and Butt Rot in Forest Trees; 1988 August; Vernon and Victoria BC; Pacific Forest Research Centre. 680 p.
- Childs, T. W., K. R. Shea, and J. L. Stewart. 1971. Elytroderma disease of ponderosa pine. USDA Forest Service Forest Pest Leaflet 42, 6 p., Washington, D.C.
- Cobb, F. W., Jr., J. R. Parmeter, Jr., D. L. Wood, and R. W. Stark. 1974. Root pathogens as agents predisposing ponderosa pine and white fir to bark beetles. p. 8-15, in. Proceedings of the 4th International Conference on Fomes annosus E. G. Kuhlman, ed. USDA Forest Service, Washington, D.C.
- Cobb, F. W., Jr., G. W. Slaughter, D. L. Rowney, and C. J. Demars. 1982. Rate of spread of Ceratocystis wagneri in ponderosa pine in the central Sierra Nevada. Phytopathology 72: 1359-1362.
- Cummins, G. B. 1984. Two new rust fungi (Uredinales). Mycotaxon 20: 617-618.
- Darker, G. D. 1932. The Hypodermataceae of conifers. Arnold Arboretum Contributions 1: 1-131.
- Darker, G. D. 1967. A revision of the genera of the Hypodermataceae. Canadian Journal of Botany 45: 1399-1444.
- Eav, B. B., and C. G. Shaw, III. 1987. The western root disease model: a status report. Proceedings of the 35th Western International Forest Disease Work Conference, p. 84-92.
- Edminster, C. B. 1978. RMYLD: Computation of yield tables for even-aged and two-storied stands. USDA Forest Service Research Paper RM-199, 26 p.
- Edminster, C. B., and F. G. Hawksworth. 1984. Modeling growth and yield of Southwestern mixed conifer stands, including the effects of dwarf mistletoe. Proceedings of the 32nd Western International Forest Disease Work Conference, p. 5-11.
- Edminster, C. B., H. T. Mowrer, R. L. Mathiasen, and F. G. Hawksworth. 1990. GENGYM: A variable density stand table projection system calibrated for mixed conifer stands in the Southwest. USDA Forest Service Rocky Mountain Station Research Paper (In press).
- Felix, L. S., J. R. Parmeter, Jr., and B. Uhrenholdt. 1974. Fomes annosus as a factor in the management of recreational

- forests. p. 2-7, in, Proceedings of the 4th International Conference on Fomes annosus, E. G. Kuhlman, ed. USDA Forest Service, Washington, D.C.
- Filip, G. M., and D. J. Goheen. 1982. Tree mortality caused by root pathogen complex in Deschutes National Forest, Oregon. *Plant Disease* 66: 240-243.
- Filip, G. M., D. J. Goheen, D. W. Johnson, and J. H. Thompson. 1989. Precommercial thinning in a ponderosa pine stand affected by Armillaria root disease: 20 years of growth and mortality in central Oregon. *Western Journal of Applied Forestry* 4: 58-59.
- Filip, G. M., and L. F. Roth. 1977. Stump injections with soil fumigants to eradicate Armillariella mellea from young-growth ponderosa pine killed by root rot. *Canadian Journal of Forest Research* 7: 226-231.
- Filip, G. M., and L. F. Roth. 1987. Seven chemicals fail to protect ponderosa pine from Armillaria root disease in central Washington. USDA Forest Service Research Note PNW-RN-460, 8 p.
- Gilbertson, R. L. 1974. Fungi that decay ponderosa pine. University of Arizona Press, Tucson, 197 p.
- Gilbertson, R. L., F. F. Lombard, and T. E. Hinds. 1968. Veluticeps berkeleyi and its decay of pine in North America. *Mycologia* 69: 29-41.
- Gilbertson, R. L., and M. Rosemeyer. 1985. Comandra blister rust on Mondell pine in Arizona. University of Arizona, Cooperative Extension Service, Arizona Plant Pathology, 3 p.
- Gladden, J. 1989. Data General Pest Model Submittal System. Fort Collins, CO: Forest Pest Management, Methods Application Group, USDA Forest Service, 228 p.
- Goheen, D. J. 1976. Verticicladiella wagnerii on Pinus ponderosa: epidemiology and interrelationships with insects. Ph.D. thesis, University of California, Berkeley.
- Graham, D. A. 1971. Evaluation of borax for prevention of annosus root rot in California. *Plant Disease Reporter* 55: 490-494.
- Hadfield, J. S., D. J. Goheen, G. M. Filip, C. L. Schmitt, and R. D. Harvey. 1986. Root diseases in Oregon and Washington conifers. USDA Forest Service, Pacific Northwest Region, Forest Pest Management Report 250-86, 27 p.
- Hagle, S. K., and D. J. Goheen. 1988. Root disease response to stand culture. Proceedings of Future forests of the Mountain West: A stand culture symposium. Wyman C. Schmidt; compiler, USDA Forest Service General Technical Report INT-243: 303-309.
- Harrington, N. H., and F. G. Hawksworth. 1989. Effects of fire and dwarf mistletoe on mortality of ponderosa pine. Fire and Management of Southwestern Natural Resources, proceedings of the symposium. USDA General Technical Report RM-(in press).
- Harrington, T. C., and F. W. Cobb, Jr. 1984. Host specialization of three morphological variants of Verticicladiella wagneri. *Phytopathology* 74: 286-290.
- Harrington, T. C., and F. W. Cobb, Jr. 1986. Varieties of Verticicladiella wagneri. *Mycologia* 78: 562-567.
- Harrington, T. C., and F. W. Cobb, Jr., Eds. 1988. Leptographium root diseases on conifers. American Phytopathological Society Press, St. Paul, MN, 149 p.
- Hawksworth, F. G. 1961. Dwarfmistletoe of ponderosa pine in the Southwest. USDA Forest Service Technical Bulletin 1246, 112 p., Washington, D.C.
- Hawksworth, F. G. 1977. The 6-Class dwarf mistletoe rating system. USDA Forest Service General Technical Report RM-48, 7 p.
- Hawksworth, F. G. 1978. Intermediate cuttings in mistletoe-infested lodgepole and southwestern ponderosa pine stands. p. 86-92, In: Proceedings of the symposium on dwarf mistletoe control through forest management, Robert F. Scharpf and John R. Parmeter, Jr., tech. coords. April 11-13, 1978. Berkeley, CA: USDA Forest Service General Technical Report PSW-31, 190 p.
- Hawksworth, F. G., and B. W. Geils. 1990. How long do dwarf mistletoe-infected ponderosa pines live? *Western Journal of Applied Forestry* 4: (in press)
- Hawksworth, F. G., and A. A. Lusher. 1956. Dwarfmistletoe survey and control on the Mescalero Apache Reservation, New Mexico. *Journal of Forestry* 54: 587-591.
- Hawksworth, F. G., and C. G. Shaw, III. 1984. Damage and loss caused by dwarf mistletoes in coniferous forests of western North America. Plant diseases: infection, damage and loss. R. K. S. Wood and G. J. Jellis, Eds. Blackwell Scientific Publications, Oxford, England, p. 285-297.

- Hawksworth, F. G., and C. G. Shaw, III. 1988. Damage and control of major diseases of ponderosa pine. p. 99-105, In: Ponderosa pine, the species and its management. Symposium Proceedings. David M. Baumgartner and James E. Lotan, eds., Spokane, WA, September 29-October 1, 1987. Washington State University, Cooperative Extension, Pullman, 281 p.
- Hawksworth, F. G., and D. Wiens. 1972. Biology and classification of dwarf mistletoes (Arceuthobium). USDA Forest Service Agricultural Handbook 401, 234 p., Washington, D.C.
- Hessburg, P. F., and J. S. Beatty. 1986. Incidence, severity, and growth losses associated with ponderosa pine dwarf mistletoe on the Lincoln National Forest, New Mexico. USDA Forest Service, Southwestern Region, Forest Pest Management Report R-3 86-5, 30 p.
- Hessburg, P. F., Sr. and E. M. Hansen. 1986. Mechanisms of intertree transmission of Verticicladiella wagnerii in young Douglas-fir. Canadian Journal of Forest Research 16: 1250-1254.
- Hessburg, P. F., Sr. and E. M. Hansen. 1987. Pathological anatomy of black stain root disease of Douglas-fir. Canadian Journal of Botany 65: 962-971.
- Hicks, B. R., F. W. Cobb, Jr., and P. L. Gersper. 1980. Isolation of Ceratocystis wagnerii from forest soil with a selective medium. Phytopathology 70: 880-883.
- Johnson, D. W. 1986. Comandra blister rust. USDA Forest Service Insect and Disease Leaflet 62, 8 p., Washington, D.C.
- Johnson, D. W., and F. G. Hawksworth. 1985. Dwarf mistletoes. Candidates for control through cultural management. USDA Forest Service General Technical Report WO-46: 48-55.
- Keener, P. D. 1962. Needle-cast and needle-blight fungi attacking species of Pinus in Southwestern forests. Proceedings of the Tenth Western International Forest Disease Work Conference, p. 34-37.
- Kliejunas, J. 1986. Frequency of Fomes annosus spread from true fir stumps to adjacent planted pines. USDA Forest Service, Pacific Southwest Region, Forest Pest Management Report 86-4, 4 p.
- Korstian, C. F., and W. H. Long. 1922. The western yellow pine mistletoe: Effect on growth and suggestions for control. USDA Agricultural Bulletin 1112, 35 p., Washington, D.C.
- Lessard, L., D. W. Johnson, T. E. Hinds, and W. H. Hoskins. 1985. Association of Armillaria root disease with mountain pine beetle infestations on the Black Hills National Forest, South Dakota. USDA Forest Service, Rocky Mountain Region, Forest Pest Management Report 85-4, 6 p.
- Lightle, P. C. 1967. Major disease problems and status of disease research in the Southwestern United States. Proceedings of the 15th. Western International Forest Disease Work Conference, p. 7-11.
- Lightle, P. C., and S. R. Andrews. 1968. Red rot in residual ponderosa pine stands on the Navajo Indian Reservation. USDA Forest Service Research Paper RM-37, 12 p.
- Lightle, P. C., and F. G. Hawksworth. 1973. Control of dwarf mistletoe in a heavily used ponderosa pine recreation forest: Grand Canyon, Arizona. USDA Forest Service Research Paper RM-106, 22 p.
- Lightle, P. C., and J. H. Thompson. 1973. Atropellis canker of pines. USDA Forest Service Forest Pest Leaflet 138, 6 p.
- Linhart, Y. B. 1988. Ecological and evolutionary studies of ponderosa pine in the Rocky Mountains. p. 77-89. In: Ponderosa pine, the species and its management, Symposium Proceedings, David M. Baumgartner and David M. Lotan, eds., September 29-October 1, 1987. Spokane, WA., Washington State University, Cooperative Extension, Pullman, 281 p.
- Livingston, W. H., A. C. Mangini, H. G. Kinzer, and M. E. Mielke. 1983. Association of root diseases and bark beetles (Coleoptera: Scolytidae) with Pinus ponderosa in New Mexico. Plant Disease 67: 674-676.
- Long, W. H. 1917. A preliminary report on the occurrence of western red rot in Pinus ponderosa. USDA Bulletin 490, 8 p., Washington, D.C.
- Maffei, H. M. 1989. Southwestern dwarf mistletoe damage to multi-aged ponderosa pine stands of the Colorado Front Range. Ph.D. Dissertation, Colorado State University, Fort Collins, 112 p.
- McKenzie, H. L., L. S. Gill, and D. E. Ellis. 1948. The Prescott scale (Matsucoccus vexillorum) and associated organisms that cause flagging injury to ponderosa pine in the Southwest. Journal of Agricultural Research 76: 33-51.
- Mielke, J. L. 1952. The rust fungus Cronartium filamentosum in Rocky Mountain ponderosa pine. Journal of Forestry 50: 395-373.

- Mielke, J. L., and R. W. Davidson. 1947. Notes on some western wood-decay fungi. *Plant Disease Reporter* 31: 27-30.
- Mielke, J. L., and R. S. Peterson. 1967. Albino Peridermium harknessii in ponderosa pine. *Plant Disease Reporter* 51: 306-309.
- Miller, P. R. 1978. Abiotic diseases. In, *Diseases of Pacific Coast conifers*. R. V. Bega, Tech. Coord. USDA Forest Service Agricultural Handbook 521: 5-41, Washington, D.C.
- Morrison, D. J. 1981. *Armillaria* root disease: a guide to disease diagnosis, development and management in British Columbia. Canadian Forestry Service, Pacific Forestry Research Center, Victoria, B. C., 15 p.
- Myers, C. A. 1974. Multipurpose silviculture in ponderosa pine stands of the Montane zone of Central Colorado. USDA Forest Service Research Paper RM-132, 15 p.
- Nicholls, T. H., L. Egeland, F. G. Hawksworth, D. W. Johnson, and M. K. Robbins. 1987. Control of dwarf mistletoes with a plant growth regulator. Symposium on Management of subalpine forests: building on 50 years of research. USDA Forest Service General Technical Report RM-149: 154-156.
- Owen, D. R. 1986. Annual Southwestern Region. Pest Conditions Report 1985. USDA Forest Service, Southwestern Region, Forest Pest Management Report R-3 96-4, 17 p.
- Parker, D. L. 1979. Integrated pest management guide. Arizona five-spined Ips, Ips lecontei Swaine, in ponderosa pine. USDA Forest Service, Southwestern Region, Forest Insect and Disease Management Report R-3 79-12, 17 p.
- Parker, D. L., J. W. Walters, and A. H. Smith. 1975. Assessment of factors causing ponderosa pine mortality on the Lincoln National Forest. USDA Forest Service, Southwestern Region, Forest Insect and Disease Management Report R-3 75-29, 19 p.
- Pearson, G. A. 1950. Management of ponderosa pine in the Southwest. USDA Forest Service Agricultural Monograph 6, 218 p., Washington, D.C.
- Peterson, R. S. 1960. Western gall rust of hard pines. USDA Forest Service Forest Pest Leaflet 50, 8 p., Washington, D.C.
- Peterson, R. S. 1967. Conifer rusts of the Southwest and Mexico. Proceedings of the 15th Western International Forest Disease Work Conference, p. 15-16.
- Peterson, R. S. 1968. Limb rust of pine: the causal fungi. *Phytopathology* 58: 309-315.
- Piirto, D. D., D. L. Crews, and H. W. Troxell. 1974. The effects of dwarf mistletoe on the wood properties of lodgepole pine. *Wood and Fiber* 6: 26-35.
- Riffle, J. W. 1967. Investigations of nematodes and mycorrhizae of marginal ponderosa pine and associated species in central New Mexico. Proceedings of the 15th Western International Forest Disease Work Conference, p. 22-27.
- Riffle, J. W. 1968. Plant-parasitic nematodes in marginal Pinus ponderosa stands in central New Mexico. *Plant Disease Reporter* 52: 52-55.
- Riffle, J. W., and G. W. Peterson, Tech. Coords., 1986. Diseases of trees in the Great Plains. USDA Forest Service General Technical Report RM-129, 149 p.
- Rogers, T. J., and H. M. Maffei. 1988. Annual Southwestern Region forest pest conditions report, 1987. USDA Forest Service, Southwestern Region, Forest Pest Management Report R-3 88-2, 15 p.
- Rogers, T. J., and H. M. Maffei. 1989. Annual Southwestern Region forest pest conditions report, 1988. USDA Forest Service, Southwestern Region, Forest Pest Management Report R-3 89-2, 18 p.
- Roth, L. F., and L. Rolph. 1978. Marking guides to reduce Armillaria root rot in ponderosa pine are effective. *Forest Science* 24: 451-454.
- Roth, L. F., L. Rolph, and S. Cooley. 1980. Identifying infected ponderosa pine stumps to reduce costs of controlling Armillaria root rot. *Journal of Forestry* 78: 145-151.
- Roth, L. F., C. G. Shaw, III, and L. Rolph. 1977. Marking ponderosa pine to combine commercial thinning and control of Armillaria root rot. *Journal of Forestry* 75: 644-647.
- Russell, K. W. 1978. Armillaria root rot: a guide for reducing and preventing losses. Division of Forest Land Management. Washington State Department of Natural Resources, 23 p.
- Scharpf, R. F., and R. V. Bega. 1981. Elytroderma disease reduces growth and vigor, increases mortality of Jeffrey pines at Lake Tahoe Basin, California. USDA Forest Service Research Paper PSW-155, 6 p.
- Scharpf, R. F., R. S. Smith, and D. Vogler. 1987. Pruning dwarf mistletoe brooms reduces stress on Jeffrey pines, Cleveland National Forest, California. USDA Forest Service Research Paper PSW-186, 7 p.

- Scharpf, R. F., R. S. Smith, and D. Vogler. 1988. Management of dwarf mistletoe in ponderosa and Jeffrey pines in forest recreation areas. USDA Forest Service General Technical Report PSW-103, 10 p.
- Scharpf, R. F., and J. R. Parmeter, Jr., Tech. Coords. 1978. Proceedings of the symposium on dwarf mistletoe control through forest management. USDA Forest Service General Technical Report PSW-31, 190 p.
- Scharpf, R. F., and M. Srago. 1974. Conifer damage and death associated with the use of highway deicing salt in the Lake Tahoe Basin of California and Nevada. USDA Forest Service Region, Forest Pest Control Technical Report 1, 16 p.
- Schubert, G. H. 1974. Silviculture of southwestern ponderosa pine: the status of our knowledge. USDA Forest Service Research Paper RM-123, 71 p.
- Shaw, C. G., III. 1980. Characteristics of Armillaria mellea on pine root systems in expanding centers of root rot. Northwest Science 54: 137-145.
- Shaw, C. G., III, D. J. Goheen, and B. B. Eav. 1989. Simulation of impacts of annosus root disease with the western root disease model. In: Proceedings of Symposium on Heterobasidion annosum, Pacific Grove, CA, April 1989. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, General Technical Report PSW- (in press).
- Shaw, C. G., III, and L. F. Roth. 1976. Persistence and distribution of a clone of Armillaria mellea in a ponderosa pine forest. Phytopathology 66: 1210-1213.
- Shaw, C. G., III, L. F. Roth, L. Rolph, and J. Hunt. 1976. Dynamics of pine and pathogen as they relate to damage in a forest attacked by Armillaria. Plant Disease Reporter 60: 214-218.
- Shaw, C. G., III, A. R. Stage, and T. M. Webb. 1985. Development of a root disease subroutine for use with stand growth models of western forests. Proceedings of the 33rd Western International Forest Disease Work Conference, p. 48-54.
- Sleavin, K. E. 1989. Data General Growth and Yield Submittal System User Guide. Version 2:34:03:89. Fort Collins, CO: Washington Office Timber Management Unit, Forest Service, U. S. Department of Agriculture; 194 p.
- Smith, R. S., Jr. 1984. Root disease-caused losses in the commercial coniferous forests of the United States. USDA Forest Service, Forest Pest Management, Methods Application Group Report 84-5, 21 p.
- Spotts, R. A., J. Altman, and J. M. Staley. 1972. Soil salinity related to ponderosa pine tipburn. Phytopathology 62: 705-708.
- Stage, A.R., C. G. Shaw, III, M. Marsden (and others). 1989. User's Guide for the Western Root Disease Model. USDA Forest Service, Intermountain Research Station General Technical Report (In Press).
- Staley, J. M. 1967. Foliage diseases of conifers in the Southwestern United States and Mexico. Proceedings of the 15th Western International Forest Disease Work Conference, p. 11-115.
- Stevens, R. E., and H. W. Flake, Jr. 1974. A roundheaded pine beetle outbreak in New Mexico, associated stand conditions, and impact. USDA Forest Service Research Note RM-259, 4 p.
- Stevens, R. E., and F. G. Hawksworth. 1970. Insects and mites associated with dwarf mistletoes. USDA Forest Service Research Paper RM-59, 12 p.
- Stevens, R. E., and F. G. Hawksworth. 1984. Insect-dwarf mistletoe associations: an update. In, Biology of Dwarf Mistletoes: Proceedings of the Symposium. Frank G. Hawksworth and Robert F. Scharpf, Tech. Coords., August 8, 1984, Fort Collins, Colorado. USDA Forest Service General Technical Report RM-111: 94-101.
- Thompson, W. G. 1940. A growth rate classification of southwestern ponderosa pine. Journal of Forestry 38: 547-553.
- USDA Forest Service. 1961. Annual Report 1960. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, 102 p.
- USDA Forest Service. 1989. Forest nursery pests. USDA Agricultural Handbook 680, Washington, D.C. (in press)
- Wagener, W. W., and J. L. Mielke. 1961. A staining-fungus root disease of ponderosa, Jeffrey, and pinon pines. Plant Disease Reporter 45: 831-835.
- Wagner, M. R., and R. L. Mathiasen. 1985. Dwarf mistletoe-pandora moth interaction and its contribution to ponderosa pine mortality in Arizona. Great Basin Naturalist 45: 423-426.
- Walters, J. W. 1977. Biological evaluation, salt damage, New Mexico State Highway 4 adjacent to Bandelier National Monument. USDA Forest Service, Southwestern Region, Forest Insect and Disease Management Report R-3 77-22, 7 p.

- Walters, J. W. 1978a. A guide to forest diseases of southwestern conifers. USDA Forest Service, Southwestern Region, Forest Insect and Disease Management Report R-3 78-9, 36 p.
- Walters, J. W. 1978b. Impact evaluation for dwarf mistletoe-infested ponderosa pine in the Southwest. p. 62-66, In: Proceedings of the symposium on dwarf mistletoe control through forest management, Robert F. Scharpf and John R. Parmeter, Jr., tech. coords. April 11-13, 1978. Berkeley, CA: USDA Forest Service General Technical Report PSW-31, 190 p.
- Wargo, P. M., and C. G. Shaw III. 1985. Armillaria root rot: The puzzle is being solved. Plant Disease 69: 826-832.
- Weiss, M. J. 1974. Annual Report, Forest Disease Detection Survey: Air pollution, Arizona and New Mexico, Region 3. USDA Forest Service, Southwestern Region, Forest Insect and Disease Management Report R-3 74-24, 26 p.
- Weiss, M. J., and J. W. Riffle. 1971. Armillaria root rot in a ponderosa pine plantation in New Mexico. Plant Disease Reporter 55: 823-824.
- Wicker, E. F., and F. G. Hawksworth. 1988. Relationships of dwarf mistletoes and intermediate stand cultural practices in the Northern Rockies. p. 298-302. In: Proceedings, Future forests of the Mountain West: A stand culture symposium. Missoula, MT., September 29-October 3, 1986. Wyman C. Schmidt, compiler, USDA Forest Service General Technical Report INT-243, 402 p.
- Wicker, E. F., and C. G. Shaw. 1967. Target area as a klendusic factor in dwarf mistletoe infections. Phytopathology 57: 116-1163.
- Williams, R. E., C. G. Shaw, III, P. M. Wargo, and W. H. Sites. 1986. Armillaria root disease. USDA Forest Service, Forest Insect and Disease Leaflet 78, 8 p., Washington, D.C.
- Wood, R. E. 1982. Biological evaluation: Root disease and southwestern dwarf mistletoe, Compartment 317.1. USDA Forest Service, Southwestern Region Forest Pest Management Report R-3 82-9, 6 p.
- Wood, R. E. 1983. Mortality caused by root diseases and associated pests on six national forests in Arizona and New Mexico. USDA Forest Service, Southwestern Region, Forest Pest Management Report R-3 83-13, 31 p.
- Worrall, J. J., J. R. Parmeter, and F. W. Cobb. 1983. Host specialization of Heterobasidion annosum. Phytopathology 73: 304-307.
- Wykoff, W. R., N. L. Crookston, and A. R. Stage. 1982. User's guide to the stand prognosis model. USDA Forest Service General Technical Report INT-133, 112 p.

Wildlife Habitat Concerns: Moderator's Comments

David R. Patton
NAU School of Forestry

A major task of the Arizona Game and Fish Department is the effective coordination of wildlife habitat needs with commercial timber sales on Arizona's National Forests. The Department's Pinetop Region uses the concepts of interdisciplinary integrated stand management to review timber sales on the Apache-Sitgreaves National Forest. The diverse habitat needs of wildlife are being evaluated by emphasizing indicator species through wildlife habitat relationships models.

Forest fragmentation in northern Arizona, as a result of logging practices in the ponderosa pine-mixed conifer forests has forced black bears to use drainages inaccessible to logging or to small isolated islands of mixed conifers. As a result, female black bears are more vulnerable to hunting. A lack of recruitment of females to the population is hindered by the loss of cubs to predators. Habitat fragmentation threatens the viability of the bear population, and the situation needs to be monitored closely.

Guidelines developed for elk summer thermal cover in the Pacific Northwest are not applicable to southwest ponderosa pine or pinyon-juniper forests. Results from 64 documented cover sites obtained from 22 radio-collared elk indicates that

a canopy closure of greater than 75% provides the best cover. A significant part of the high-quality cover was provided by Gambel oak.

Porcupines and Abert squirrels both consume parts of ponderosa pine trees, with the Abert squirrel being more specialized than the porcupine. However, feeding by both species is concentrated on specific trees. Patterns of utilization are different for the two species, so that individual trees are seldom fed upon by both. Evidence suggests that differential utilization of trees is associated with variations in levels of certain elements, carbohydrates, and monoterpene composition of resins.

In National Forest plans, "adjacency constraints" are defined stipulating that stands of a single age class cannot be adjacent to certain other age classes. The intention is to provide a diverse habitat for wildlife as forest regulation is accomplished. Strict adherence to constraints for enhancing horizontal and vertical diversity of tree overstory is not feasible. An index of spatial and temporal diversity may offer a simpler solution if well-defined deviations from adjacency constraints are allowed to occur during a rotation.

Integrating Wildlife Needs into National Forest Timber Sale Planning: A State Agency Perspective¹

Norris L. Dodd and Sharen L. Adams²

Abstract.--The Arizona Game and Fish Department (AGFD) has maintained a strong commitment to effective integration of wildlife needs into National Forest timber sale planning, particularly since the inception of Integrated Stand Management (ISM). This paper addresses AGFD timber sale coordination efforts on the Apache-Sitgreaves National Forests. Based upon the development of 56 sales since 1984, an evaluation of ISM sale planning is provided. Emerging timber management issues relating to applications of ISM which may impact wildlife integration of timber sales are addressed.

INTRODUCTION

The harvest of timber from National Forest timberlands has long been recognized as a viable and cost effective means to achieve desired wildlife habitat conditions and objectives (Thomas 1979, Hoover and Wills 1984). The key to effectively meeting the needs of a wide variety of wildlife species through planned timber harvest lies in the clear identification of issues and concerns, and translation of these into measurable objectives to be integrated through the sale planning process.

The Arizona Game and Fish Department (AGFD), through its aggressive Environmental Evaluation Program, has made a significant commitment to effective integration of wildlife needs in timber sale planning since the inception of its program 10 years ago. Timber management in Arizona is rapidly evolving, forcing habitat managers to monitor and evaluate past practices and address new issues and concerns. In addition, the complexity

of achieving effective integration of timber sales is increasing dramatically, influenced by both biological and socioeconomic factors.

This paper addresses past and present integration efforts on the Apache-Sitgreaves National Forests, for which timber coordination efforts are the responsibility of the AGFD's Pinetop Region. The objectives of this paper are to:

- 1) detail Pinetop Region AGFD timber coordination and wildlife integration activities,
- 2) provide a preliminary evaluation of the application of Integrated Stand Management to timber sale planning since its inception,
- 3) identify and discuss newly emerging issues and concerns relating to current timber sale planning and implementation, and
- 4) present recommendations to ensure that timber management will continue to yield benefits to the wildlife resource.

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²Norris L. Dodd and Sharen L. Adams are both Regional Habitat Specialists with the Arizona Game and Fish Department, Pinetop, AZ.

ANALYSIS AREA AND MANAGEMENT BACKGROUND

The Apache-Sitgreaves National Forests (A-S NFs) are located in east-central Arizona, and encompass 810,826 hectares (2,003,552 acres). The two forests were proclaimed as separate

forests in 1908, formed from the Black Mesa National Forest, itself established from the 1889 Black Mesa Forest Reserve. The two forests were consolidated administratively under a single Supervisor's Office in 1974.

The A-S NFs lie within the Colorado Plateau physiographic province, characterized by nearly flat bedded sedimentary rock generally bordered by the Mogollon Rim escarpment. The Mogollon Rim forms the southern boundary of the Sitgreaves NF and splits the Apache NF. Elevations range from 1704-3665 meters (5300-11,400 feet).

Landforms of the Sitgreaves NF are dominated by broad upland plains, hills formed from sedimentary deposits, and ridges and canyons formed by downcutting by tributaries of the Little Colorado River. The eastern portion of the Sitgreaves NF and entire Apache NF are more complex due to the prevalence of Datil volcanic fields. Landforms include upland plains, hills, ridges, scarps, mountains and numerous cindercone knolls. The Apache NF makes a significant contribution to the water needs of metropolitan Phoenix, as it is drained by the Little Colorado, San Francisco and Black rivers.

Vegetation of the A-S NFs is diverse due to wide variations in elevation, climate and soils. The most prevalent vegetative type is Ponderosa pine, which comprises 41% of the forests, followed by pinyon-juniper (38%), mixed conifer (8%), grasslands, both mountain (7%) and semi-desert (3%), and spruce-fir (2%) (USDA 1987). The forests support a tremendous riparian and fishery resource, though it comprises less than 1% of the land area.

The A-S NFs support 411 species of wildlife, reflective of the area's high vegetative, climatic and physical diversity. This assemblage includes 28 fish, 12 amphibian, 35 reptile, 242 bird and 94 mammal species (USDA 1987). Of these, 30 are afforded status as Federally- or State-listed threatened or endangered species (AGFD 1988a). Wildlife related recreation on the A-S NFs is significant, illustrated best by their status as fifth among all 156 national forests in cold water fishing recreation (Everest and Summers 1982). This fishing-related recreation contributes nearly \$27,000,000 to local economics (AGFD 1986).

The A-S NFs yield the highest production of commercial timber of the 11 National Forests in Arizona and New

Mexico, with an Allowable Sale Quantity (ASQ) of 99 million board feet (mmbf) per year. This ASQ represents a 53% increase over historic 10-year (1973-84) harvest levels (USDA 1987). Several large and small mills depend on commercial timber from the A-S NFs.

Management of the A-S NFs is guided by their Land and Resource Management Plan (USDA 1987), as mandated by the National Forest Management Act (NFMA). This controversial Forests Plan has focused considerable attention on management change on the forests, due partly to its strong emphasis on wildlife, fisheries, riparian and recreation. Through its setting of an ASQ well above historic harvest levels, the Forests Plan also maintains a strong focus on timber production on the forests. This plan was appealed in 1987 by six entities, including the AGFD, with the appeals remaining unresolved to date. Much of the focus of the six appeals relates to timber management of the forests, including the ASQ, old growth management and uneven- vs. even-aged management. Primary appellants concerned with such timber issues are currently involved in mediation in an effort to reach resolution.

Lastly, to gain a better understanding of both the relationships of biological and socio-economic influences on timber management on the A-S NFs, it is important to chronicle changes on the timber market as they relate to effective multiple resource integration of timber sales. At the time of the inception of Integrated Stand Management (ISM), a radical new approach to timber sale planning and implementation by the Southwestern Region (Arizona and New Mexico) of the Forest Service in 1984, the timber market was in an extremely depressed state.

Timber sales offered by the A-S NFs often went unsold, many under contract were not being cut until such time that the market rebounded, or were sold back to the Forest Service under its "buy back" program. Consequently, the ISM process proved highly successful in providing for the development of sales which creatively addressed multiple resource objectives and needs, with the emphasis on timber volume outputs being somewhat secondary.

However, in 1987 the timber market began a steady recovery, followed in 1988 by the first bidding and purchase of National Forest timber by the Fort Apache Timber Company (FATCO). FATCO had

historically relied totally on timber from the White Mountain Apache Reservation, located adjacent to the A-S NFs. Due to past cutting above sustained yield levels, and ongoing litigation with the Federal government, FATCO began successfully bidding and purchasing several sales on the A-S NFs in 1988 and 1989, with their stated desires to obtain 40 mmbf (40% of the A-S NFs' ASQ) off the Reservation. This served to dramatically alter the historic demand situation among traditional A-S NFs timber purchases.

Coinciding with the dramatically increased demand situation was the continually improving timber market, which served to further exacerbate the demand situation among purchasers on the A-S NFs. Up until this point, in mid-1989, many sales developed under ISM were realizing shortfalls in achieving Forests Plan volume targets on the order of 10 to 25%, and as high as 55%, reflective of effectively integrating multiple resource objectives, on-the-ground application of Forests Plan standards and guidelines, and actual available timber volumes.

At this point in time, with the unprecedented demand for timber from the A-S NFs and a strong timber market, the ability to continue to creatively develop sales with an emphasis on multiple resource objective achievement remains unclear. As will be discussed later, increasing emphasis is being placed on the attainment of timber volume targets and meeting the forests' ASQ. Such socio-economic considerations are now resulting in increased levels of conflict in timber sale planning and realization of new issues and concerns as sales developed under IRM are now being implemented.

DEPARTMENT TIMBER COORDINATION ACTIVITIES

The AGFD has long attempted to maintain a strong involvement and commitment to positive and proactive timber sale planning and coordination on Arizona's national forests. The Pinetop Region of the AGFD has interacted to a very high degree with the A-S NFs, particularly since the inception of ISM on the forests in 1984. Since formal adoption of Integrated Resource Management (IRM) as the Southwestern Region's project implementation and National Environmental Policy Act (NEPA) compliance process (USDA 1988), the Pinetop Region has interacted with the A-S NFs through this important vehicle.

IRM constitutes a 13-phase planning process by which Forest Service projects, including timber sales, are developed based upon key issues, concerns, and objectives, incorporating public involvement. In addition to the IRM process, AGFD timber coordination activities are conducted under authority of the AGFD-Forest Service Memorandum of Understanding, Sikes Act as amended in 1974, and specific Forest Service Manual supplements. Aggressive timber integration activities on the part of the AGFD are often perceived as going far beyond the traditional responsibilities of the state agency for wildlife and the Forest Service for habitat. The AGFD, through its committed habitat coordination endeavors, recognizes the inextricable link between effectively managing habitat and maintaining diverse and viable wildlife populations.

Critical to effectively influencing the outcome of timber sale planning from a wildlife perspective is having a strong understanding of the A-S NFs Forests Plan standards and guidelines. A crucial step in the IRM process is the initial scoping and identification of issues, concerns and objectives for wildlife for a specific proposed timber sale area. This information is crucial as it will ultimately drive the development of alternatives under IRM, and is obtained through extensive reconnaissance of the sale area and documented in letter format.

The effective and clear setting of objectives for a wide range of wildlife species is also of paramount importance. The ability to set measurable or quantifiable objectives tied to current habitat conditions and wildlife species present is considered to have been a key element to effective integration of timber sales over the past 5 years under ISM. In attempting to quantify and document current and desired habitat conditions, AGFD personnel rely on intensive reconnaissance to make assessments of forage to cover relationships for big game, critical habitats (e.g. riparian, old growth), horizontal diversity and spatial relationships. Other factors such as road densities and fuels treatment integration needs are also considered.

One tool which has proven useful in quantifying existing habitat conditions is the Southwestern Region's Wildlife-Habitat Relationships Model (USDA 1984). This model allows for the assessment of habitat capability conditions relative to potential for "indicator species", based on intensive inventory of structural stages (e.g. grass/forb, seedling/sapling,

pole, mature, old growth). This model has been modified continuously since 1985 to incorporate the best information available for the indicator or emphasis species, and better reflect the impact of conversion from uneven- to even-aged stands under even-aged management.

In spite of the limitations to utilizing a management indicator species approach to assessing timber sale relationships (Patton 1987), the wildlife-habitat relationships model has exhibited a high degree of utility in helping assess existing habitat conditions for a variety of species ranging from those often benefiting from moderate levels of timber harvest [e.g., elk (*Cervus elaphus*)] to those typically negatively impacted [e.g., goshawk (*Accipiter gentilis*)]. Clearly, managers cannot address the impact of timber harvest on all 411 wildlife species inhabiting the A-S NFs. The range of species for which existing conditions are assessed depends directly on those present within the specific proposed timber sale area and the level of concern raised during field reconnaissance. Typically, objectives are identified and evaluated on each proposed sale area for a mix of early and late seral big game, small game, nongame and sensitive, threatened or endangered species.

The greatest utility of the wildlife-habitat relationships model and other assessments is in providing a baseline of existing conditions such that quantifiable objectives for timber harvest may be derived and compared during the alternative development phases of IRM. Limitations of modeling, particularly the inability to incorporate or display spatial relationships must be addressed through mapping and other analyses. Computerized Geographic Information System (GIS) analyses are just now being employed by the AGFD to help in evaluating timber sale alternatives.

The relative degree to which various timber sale harvest alternatives address key issues and concerns and meet quantifiable objectives serves as the basis for AGFD evaluation of such alternatives, as well as justifying the modification of alternatives to better address wildlife needs. In proposing its own alternatives or recommending the modification of existing ones, the AGFD has focused on the development of integrated alternatives as opposed to the development of pure wildlife alternatives. Such efforts have been largely successful due to the setting and attainment of wildlife objectives within the context of also meeting other resource

objectives. Silvicultural needs are considered in the development or modification of alternatives, such as the treatment of high priority stands infected with dwarf mistletoe to create effective wildlife foraging areas.

Considerable complexity exists in timber sale planning under IRM where attempts are made to effectively integrate all resources, considering sawtimber harvest, commercial and precommercial thinning, road management, fuels treatment, post-sale Knutson-Vandenburg Act projects, old growth inventory and effective assessments of cumulative effects.

Should the IRM process fail to adequately address issues and concerns or document the selection of one alternative over others through NEPA environmental analysis, timber coordination may be relegated to more reactive measures (e.g., administrative appeal; AGFD 1989). The benefits of positive and proactive approaches to timber sale coordination have the potential to yield far more benefits for the wildlife resource than such reactive measures.

EVALUATION OF INTEGRATED STAND MANAGEMENT

Since the implementation of ISM in 1984 by the Southwestern Region of the Forest Service, representing a significant change over previous approaches to timber management, the AGFD's Pinetop Region has participated in the development of 56 sales on the A-S NFs. Of these, 12 have been carried through the final stages of implementation, with timber harvest completed by the purchasers.

Monitoring of these sales, as well as the insights gained from coordinating to a high degree in the development of all sales produced under ISM and IRM, affords the opportunity to assess the utility and value of these approaches to timber sale planning. All too often, management practices and their results fail to be adequately monitored and assessed. However, in this case, with the controversies over timber management on the A-S NFs growing, monitoring of ISM applications is deemed essential if effective resolution of timber issues is to be attained.

ISM differs significantly from previous approaches to timber sale planning for several reasons. Most importantly, it is predicated upon the premise that all forest resources are intricately linked. Clearly stated

objectives for all resources, considered collectively, guide the development of harvest alternatives. This differs from earlier approaches, as timber goals and objectives typically drove the process, with other resources considered secondarily, usually through mitigation measures. The potential for success under ISM relates to the strong interdisciplinary approach taken by the A-S NFs, involving all interested publics, including the AGFD.

Previous to ISM, timber harvest generally was applied to a majority of a particular timber sale area, often as high as 90% of the sale area. However, in most instances, particularly within the Ponderosa pine vegetation type, harvest levels were relatively light. These harvest regimes have often been referred to as "pick and pluck", and resulted in post-harvest conditions similar to that of individual tree selection under uneven-aged management systems. In general, relatively low volumes were yielded off relatively large portions of the timber sale areas.

With the advent of ISM, the harvest situation has been altered dramatically. First, treatments have been confined to a smaller portion of the timber sale areas, generally between 40 to 50% of the total forested acres. However, these areas are treated quite heavily, typically done from a pure silvicultural diagnosis standpoint. To date, nearly all treatments on the A-S NFs planned under ISM have been under even-aged management, with virtually no flexibility realized to even meet specific uneven-aged management objectives. Hopefully, this situation will be alleviated through amendment of the Forests Plan.

With the focus of timber harvest under ISM on even-aged management, the achievement of wildlife objectives has been addressed primarily through maximization of horizontal diversity and edge effect (Thomas 1979). In addition, a strong reliance on the relatively high proportion of the sale areas deferred from harvest has served to meet wildlife needs for old growth, thermal and hiding cover, vertical diversity, and has helped create effective mosaics of vegetation structural stages.

Under ISM, the vehicle for maximizing horizontal diversity with intensive even-aged prescriptions has been the limitation of stand sizes to 100 acres (La Follette 1981), with the exception of areas managed for old growth. Utilizing small stands, mosaics of moderate to heavily treated

stands have been juxtaposed next to deferred stands to create effective forage to cover relationships. Edge effect has been maximized to create high levels of contrast between adjacent stands, dispersion of stands exhibiting differing structural conditions, and irregularity in shape. In these regards, ISM has proven successful in the vast majority of cases in achieving multiple wildlife objectives through the maximization of horizontal diversity and deferral of adequate old growth and cover areas.

Implied under ISM, with the emphasis on even-aged management and heavy silvicultural treatments, was adequate periods between reentry into sale areas to allow for growth of treated stands, regeneration of seed cuts to create new hiding cover stands, and effective wildlife use of created habitat mosaics. Forests Plan standards and guidelines stipulate, for instance, that adjacent stands exhibit 20 year age class differences. Where portions of large, homogeneous stands are treated heavily to create desired edge effect and structural diversity, induced diversity may be lost with subsequent heavy treatment of adjacent stands with insufficient time allowed between reentries.

Where it was believed that reentries into sale areas would be on the order of 12 to 15 years, or even 20 years, reentries into sale areas are already being planned as short as five years following previous harvest. With growing concern over the timber demand situation and efforts to meet the forests' ASQ, reentries into many sale areas have the potential to be dramatically hastened. Under the intensive silvicultural treatments programmed under ISM, residual stand basal areas are typically reduced to 30 to 40, with substantial effort made to convert uneven-aged stands to even-aged in a single entry. Consequently, the majority of treated stands will yield virtually no available volumes under shortened reentry periods. Hence, adjacent deferred areas then would appear to be the only place to seek volume to support the next entry. Also, due to the current designs being implemented for most integrated sales, premature reentry will eliminate diversity enhanced through the current entry and further reduce reservoirs of relatively dense, uneven-aged timber.

The premise that a relatively small proportion of the timber sale areas are treated intensively under ISM while retaining adequate amounts of untreated area to meet wildlife needs appears to be

unraveling as greater emphasis is again being placed on meeting increased timber demand. This then, represents the greatest potential threat to the ISM approach to timber sale planning, which has proven to be valuable in integrating the needs of a variety of resources into timber harvest.

EMERGING TIMBER ISSUES AND CONCERNS

After five years of planning and finally beginning to see implementation of timber sales developed under ISM on the A-S NFs, several important issues and concerns are now surfacing. Some represent issues which have arisen only recently, while others have faced resource managers for many years but are being heightened due to increased emphasis on meeting timber demands. These issues must be addressed at a variety of levels including research, effective project implementation, and resolution of appeals of the A-S NFs Forests Plan. Prompt attention must be paid to attempting to seek resolution such that adequate flexibility in forest resource management is maintained into the next century.

Major issues needing to be addressed relative to timber management include:

- 1) increasing emphasis on achieving the forests' timber ASQ to meet timber demand,
- 2) emphasis placed on even- vs. uneven-aged management systems,
- 3) increasing application of stand area designation marking in sale implementation, and
- 4) achieving effective integration of all timber management activities,
- 5) effective monitoring of timber sale implementation and impact on wildlife.

Increasing Emphasis on Achieving the Forests' ASQ to Meet Timber Demand

Under applications of ISM on the A-S NFs, the forests have been offering only approximately 90mmbf of their 99mmbf annual ASQ. This is largely a result of shortfalls realized in meeting the Forests Plan 10-year offering schedule target volumes. These shortfalls have occurred due to application of Forests Plan standards and guidelines, effective integration of multiple resource objectives, and actual available timber

volumes being less than predicted. Nonetheless, with the timber market now very strong, coupled with the unprecedented timber demand situation on the A-S NFs, intense pressure is now being realized to meet timber volume targets and achieve the forests' ASQ. In fact, the ASQ, which is believed to represent a timber offering ceiling as set forth in NFMA, is now being considered as a commitment that must be met. Treating the ASQ as such now has the potential to have an impact on the creative development of quality timber sales under ISM.

Considerable attention is currently being given by the Forest Service to potential advancement of timber sales in the A-S NFs 10-year offering schedule to address the need to meet their ASQ. This is occurring despite the fact that the ASQ itself is a point of much contention in the ongoing Forests Plan appeals.

Concerns relating to the A-S NFs' ASQ include the cumulative or additive impact of the various levels of modeling used to generate the forests' ASQ and subsequent disaggregation to the 10-year offering schedule. The growth and yield model (ECOSIM) employed to drive the FORPLAN resource allocation model has been demonstrated to have numerous limitations (Belcher et al. 1982, McTague 1986). The FORPLAN model is further believed to have not been adequately constrained to account for adequate acreage managed for old growth, big game hiding cover, stand adjacency constraints, or uneven-aged management (AGFD 1988b).

Other concerns with the A-S NFs' ASQ relate to silvicultural limitations and Forests Plan standards and guidelines which may preclude meeting timber targets. The ability to meet nondeclining even flow requirements under NFMA is yet another concern with the current ASQ (AGFD 1988b). Consequently, considerable concern exists relative to the ability to maintain long-term community economic stability with current levels of harvest, and especially with potential advanced offering and harvest.

With the move toward an advanced timber offering schedule on the forests, coupled with the experience gained from numerous ISM applications, the AGFD harbors additional concerns relative to the forests' ASQ. Treating the ASQ as a "commitment" to industry will no doubt compromise the ability of ISM and IRM to produce quality projects which effectively address multiple resource objectives. There may be significantly increased cumulative effects with timber sale

offering advancement, including shortened periods between entries (as short as 5 to 7 years), resulting in the inability to meet wildlife standards and guidelines over time. In addition, concern exists over increased watershed degradation and ability to maintain viable and diverse wildlife populations.

The potential cumulative effects of past, present and future timber harvest on wildlife and other resources are just now being realized. Already, many sale areas for which sales have been developed or implemented are experiencing difficulty or inability to meet target volumes and Forests Plan standards and guidelines. With volumes maximized through heavy silvicultural treatments, such areas will not exhibit timber growth sufficient to support reentry within 10 to 15 years and still meet wildlife needs.

In many instances on sales currently being implemented, wildlife standards and guidelines are just minimally being met, particularly for harvest sensitive species such as the goshawk or Abert squirrel (*Sciurus aberti*). The Abert squirrel appears to be particularly sensitive to repeated entries under various silvicultural treatments which both open stands up and reduce or eliminate within-stand clumpiness or vertical diversity through even-aged management. Big game forage to cover ratios have often been minimally met under current timber sales developed under ISM, with effective cover becoming limiting. Without adequate time between entries, the cumulative effects of the next entry will be realized as wildlife standards and guidelines will be reduced below minimums. Advanced offering of sales to meet the ASQ will only exacerbate this situation due to shortened reentry periods.

The integrity of the A-S NFs' remaining old growth resource and biological diversity is also a major area of concern with potential advanced timber harvest. The Forests Plan ASQ was predicated upon liquidating much of the remaining old growth on the Apache NF and managing old growth on a "rotation basis" across both forests. However, both the Society of American Foresters (1984) and The Wildlife Society (Thomas et al. 1988) question the merits of creating, through silvicultural treatment, replacement stands of old growth to replace liquidated existing old growth. The impact of such proposed old growth management on dependent wildlife species (e.g., goshawk) is an area of particular concern. Alternative approaches to old growth management which retain existing

reservoirs of biological diversity and management options into the future are a priority need.

Emphasis Placed on Even- vs. Uneven-aged Management Systems

As discussed earlier, ISM was predicated on predominately treating stands under even-aged management systems, such that horizontal diversity is maximized for wildlife. However, as sales have been implemented, the need for flexibility to treat stands under uneven-aged management systems has become apparent.

Southwestern Ponderosa pine forests typically developed over time as irregular uneven-aged stands (Pearson 1950), and associated wildlife species coevolved under such conditions. In fact, species for which information suggests that uneven-aged management is preferable include the goshawk (Reynolds 1983), Abert squirrel (Patton 1975), black bear (*Ursus americanus*; Mollohan 1987) and Merriam's turkey (*Meleagris gallopavo*; Phillips 1982). The Society of American Foresters (1981) has also promoted uneven-aged management as a means to maintain or enhance wildlife values under timber harvest.

Uneven-aged management has been reported as a viable and economic method to manage Ponderosa pine forests and achieve multiple resource objectives (Schubert 1974, Hann and Bare 1979). Uneven-aged management is crucial to the management and creation of potential old growth, if such conditions can indeed be created. The current emphasis on even-aged management must be relaxed, with adequate flexibility available to practice uneven-aged management where appropriate. An approach where both even- and uneven-aged management systems are employed to create a mix of areas exhibiting horizontal and vertical diversity conditions now appears in order.

Increasing Application of Stand Area Designation Marking

With the intensive silvicultural treatments being applied under ISM, stand conditions are often dramatically altered in terms of structural diversity and age class mix. This is especially true under even-aged management treatments such as final removal and seed cut prescriptions. Many stands within integrated sales are now being implemented with stand boundary/area designation

marking (e.g., final removal of all trees 9" diameter at breast height and greater), where cutters are allowed to take all trees above the prescribed size. Individual trees in such stands are no longer marked for harvest by marking crews, nor are these crews providing the invaluable benefit of helping meet special wildlife habitat needs.

In the absence of specific efforts to survey and protect special wildlife habitat needs such as raptor nests, recruitment snags, turkey roosts, tree squirrel nest clumps, etc., these special features are not being located and protected under stand area designation marking. Such marking has constituted as much as 50 to 60% of some sale area treated acres. It is assumed that deferred stands will help address these needs, but as discussed earlier, once deferred stands are treated in the next entry, the special needs of wildlife will have been eliminated. Again, the intensive even-aged approach to harvesting timber may have potential long-term impact if these special wildlife habitat considerations are not adequately addressed.

Achieving Effective Integration of All Timber Management Activities

With the intensity of timber sale planning increasing on the A-S NFs, the need to achieve effective integration of all phases of silvicultural treatment has become evident. In the past, timber sales offering sawtimber were planned, sold and cut separately from pulpwood. Pulpwood was sold through the long-term Colorado Plateau Pulpwood Contract, which expired this year. Consequently, sales have been planned and implemented for sawtimber, with all post-sale activities completed, only to be reopened soon after for commercial thinning. This resulted in extending the periods under which the sale areas are subjected to harvest activities and associated impact to wildlife. This approach has also resulted in redundancy in timber planning and implementation, and has made effective integration and tracking between sawtimber and commercial and precommercial thinning difficult. Also, it has added considerably to cumulative impact to wildlife, fisheries, soils, watershed and other resources.

In several instances, objectives met for wildlife under sawtimber sale development have been negated at a later date when, for instance, stands deferred for hiding or thermal cover, were treated for pulpwood or precommercially thinned.

Toward achieving effective integration of all silvicultural activities, comprehensive integrated planning must be accomplished. The ideal situation would be one where all silvicultural needs are applied through a single planning effort and entry. Such a situation would allow the sale to be closed out until such time that reentry is warranted, reducing cumulative effects and providing for cost-effective sale implementation. Hopefully, this issue will be adequately addressed through Forests Plan amendment.

Effective Monitoring of Timber Sale Implementation and Impact on Wildlife

Monitoring of Forests Plan implementation is a requirement for which inadequate resources or commitment have been realized. Monitoring is necessary to evaluate whether sale layout is achieved as planned, and whether special wildlife mitigation measures were provided for. It is also necessary to determine the degree to which habitat objectives were met with timber harvest.

Due to the reliance on the wildlife-habitat relationships model to assess habitat conditions and evaluate alternatives, timely monitoring and evaluation of the model should be accomplished. Without effective monitoring, the identification and ability to address new issues and concerns, such as those raised here, would not be possible. Increased emphasis must be given to monitoring timber sale implementation and the impact to the wildlife resource.

CONCLUSIONS

In spite of great strides made in achieving multiple resource objectives through timber harvest on the A-S NFs, considerable concern still exists surrounding timber management here. Timber management must be responsive to new issues and concerns, including incorporating the flexibility to apply uneven-aged management where needed, and not treating the ASQ in a rigid manner.

Under the intensive timber program on the A-S NFs today, the prospect of reduced abilities to maintain or enhance wildlife habitat conditions into the future are unclear, at best. The cumulative effects of past, present and future harvest and associated activities are a growing concern. With the prospect of advanced harvest to meet the forests' ASQ under heavy application of intensive even-aged

management systems, wildlife habitat diversity may be reduced.

With the current emphasis on maximizing horizontal diversity at the expense of vertical diversity through even-aged management, diversity needs will be adequately maintained on the short-term. However, with reentry into sale areas where deferred areas are treated prematurely, horizontal diversity may ultimately be reduced or eliminated on the long-term. Associated with this may be the loss of special habitat components, such as raptor nests, turkey roosts and the like, if adequate measures are not aggressively taken to ensure their protection under heavy timber treatment.

Many of the issues relating to the ASQ and management of old growth and how they may affect wildlife populations may be addressed effectively with the aggressive application of new decision support systems, such as Northern Arizona University's Terrestrial Ecosystem Analysis and Modeling System (TEAMS; Covington et al. 1988). Such a project level interdisciplinary model employing GIS and timber growth and yield capabilities, as well as the ability to integrate wildlife habitat constraints, shows considerable potential to help address complex timber management issues.

The complexity of timber sale planning is increasing rapidly, influenced by a variety of biological and socio-economic factors. Through committed proactive and positive efforts, the AGFD will continue its endeavor to ensure that National Forest timber sales are developed in a manner so as to yield benefits to Arizona's diverse wildlife populations.

LITERATURE CITED

- Arizona Game and Fish Department. 1989. Appeal of the decision notice and environmental assessment for the Double Cabin Timber Sale, Chevelon Ranger District, Coconino County, Arizona. Unpublished report on file. Phoenix. 19p.
- Arizona Game and Fish Department. 1988a. Threatened native wildlife in Arizona. Arizona Game and Fish Department Publication. Phoenix. 32p.
- Arizona Game and Fish Department. 1988b. Statement of reasons in support of an appeal of the Apache-Sitgreaves National Forests Land and Resource Management Plan. Unpublished report on file. Phoenix. 43p.
- Arizona Game and Fish Department. 1986. Arizona cold water fisheries strategic plan, 1985-1990. Fed. Aid Project FW-11-R. Phoenix. 50p.
- Belcher, D.W., M.R. Holloway, and G.J. Brand. 1982. A description of STEMS-the stand and tree modeling system. USDA Forest Service Gen. Tech. Report NC-79. 7p.
- Covington, W.W., D.B. Wood, D.L. Young, D.P. Dykstra, and L.D. Garrett. 1988. TEAMS: A decision support system for multiresource management. J. For. 86(8):25-33.
- Everest, F.H. and P.B. Summers. 1982. The sportfishing resource of the national forests-its extent, recreational use, and value. USDA Forest Service. Washington, D.C. 50p.
- Hann, D.W. and B.B. Bare. 1979. Uneven-aged forest management: state of the art (or science?). USDA Forest Service Gen. Tech. Report INT-50. 18p.
- Hoover, R.L. and D.L. Wills, ed. 1984. Managing forested lands for wildlife. Colorado Division of Wildlife in cooperation with USDA Forest Service, Rocky Mountain Region. Denver, CO. 459p.
- La Follette, C. 1981. A pilot plan for forest diversity: Bureau of Land Management at Coos Bay. Cascade Holistic Economic Consultants Forestry Research Paper No. 9. Eugene, OR. 65p.
- McTague, J.P. 1986. Research proposal for the development of a new growth and yield model for ponderosa pine in the Southwest. School of Forestry. Northern Arizona University, Flagstaff. 23p.
- Mollohan, C.A. 1987. Black bear habitat use in northern Arizona. Arizona Game and Fish Department. Fed. Aid Project W-78-R, WP4, Job 19. Phoenix. 37p.
- Patton, D.R. 1987. Is the use of "management indicator species" feasible? West. J. Amer. For. 2(1):33-34.
- Patton, D.R. 1975. Abert squirrel cover requirements in southwestern ponderosa pine. USDA Forest Service Research Paper RM-145. 12p.
- Pearson, G.A. 1950. Management of ponderosa pine in the Southwest. USDA Forest Service Monograph No. 6. Washington, D.C. 218p.
- Phillips, F. 1982. Wild turkey investigations and management recommendations for the Bill Williams Mountain area. Arizona Game and Fish Department Special Report No. 13. Phoenix. 50p.
- Schubert, G.H. 1974. Silviculture of southwestern ponderosa pine: the status of our knowledge. USDA Forest Service Research Paper RM-123. 71p.

- Society of American Foresters. 1984. Scheduling the harvest of old growth. Bethesda, MD. 44p.
- Society of American Foresters. 1981. Choices in silviculture for American forests. Bethesda, MD. 80p.
- Thomas, J.W., ed. 1979. Wildlife habitats in managed forests: the Blue Mountains of Oregon and Washington. USDA Forest Service Agri. Handb. 553. 512p.
- Thomas, J.W., L.F. Ruggiero, R.W. Mannan, J.W. Schoen, and R.A. Lancia. 1988. Management and conservation of old-growth forests in the United States. Wildl. Soc. Bull. 16(3):252-262.
- U.S. Department of Agriculture, Forest Service. 1988. Project implementation process for Integrated Resource Management. Albuquerque, NM. 36p.
- U.S. Department of Agriculture, Forest Service. 1987. Apache-Sitgreaves National Forests Plan. Springerville, AZ. 295p.
- U.S. Department of Agriculture, Forest Service. 1984. Wildlife coefficients technical report. Springerville, AZ 55p.

The Influence of Animals on Genetic Variability Within Ponderosa Pine Stands, Illustrated by the Effects of Abert's Squirrel and Porcupine¹

Yan B. Linhart, Marc A. Snyder, and Susan A. Habeck²

Abstract.--Mammals, insects and parasites can be important agents of natural selection in ponderosa pine forests. We illustrate the selective effects of animals by describing feeding patterns of the Abert's squirrel (*Sciurus aberti*) and the porcupine (*Erethizon dorsatum*). Each animal shows evidence of selective feeding upon specific host individuals. Both animals damage the trees they feed upon, and can therefore act as agents of natural selection. Because of their differential feeding patterns, these species can generate diversifying selection within stands.

INTRODUCTION

Ponderosa pine (*Pinus ponderosa* Laws.) is a major contributor to the volume of lumber cut in North America. Because of this, management strategies have usually sought to maximize harvestable yields, and research has focused upon geographical areas which provide the greatest amounts of lumber: primarily stands in northern California, Oregon, Washington, Idaho, and western Montana. In other parts of its range, ponderosa pine is a much smaller, irregularly-shaped tree, and its contribution to local lumber industries is modest to non-existent. Its value in these areas has sometimes been overlooked.

Although many southwestern ponderosa pine forests produce modest volumes of timber, they are valuable in a variety of other contexts, and therefore must be managed for multiple uses, including watershed protection, recreation, and wildlife habitat. For example, the Rocky Mountains in Colorado give rise to five of the most important western rivers: the North Platte, South Platte, Arkansas, Rio Grande, and Colorado. Ponderosa pine forests are important components of these watersheds in many places. Furthermore, in Colorado, ponderosa pine-dominated stands comprise the forest zone most heavily used for recreation (Myers 1974). Natural forests that include native inhabitants, especially the more visible birds and mammals, are important in this context.

In this paper, we propose that the maintenance of genetic variability within ponderosa pine stands is essential to the health of these stands, and should therefore be a primary management objective. We relate the ecological complexity observed in these pine forests to their genetic complexity. To

illustrate the relationship between ecology and genetics, we focus on feeding patterns of two mammals, Abert's squirrels (*Sciurus aberti*) and porcupines (*Erethizon dorsatum*). In the process, we suggest that diversifying selection can be generated by these herbivores within ponderosa pine stands.

In the next sections we discuss:

1. Factors shaping genetic variability in ponderosa pine
2. Abert's squirrel feeding patterns
3. Porcupine feeding patterns
4. Differential utilization of ponderosa pine phloem by Abert's squirrels and porcupines
5. Management implications

FACTORS SHAPING GENETIC VARIABILITY IN PONDEROSA PINE

Ponderosa pine has the most extensive geographic range of all North American conifers. The species has been separated into three major taxonomic entities, variety *ponderosa*, var. *scopulorum*, and var. *arizonica*. Increasingly, *P. ponderosa* var. *arizonica* is being recognized as a separate species, *P. arizonica* Engelm. (Conkle and Critchfield 1988). From biochemical, morphological and physiological perspectives, a total of five races have been identified: three are within *P. ponderosa* var. *ponderosa* (Pacific, Southern California, and North Plateau), and two are within *P. ponderosa* var. *scopulorum* (Rocky Mountain and Southwestern) (see Conkle and Critchfield 1988 for details). In mountainous regions, ponderosa pine is also differentiated elevationally, as documented in California (Callahan and Liddicoet 1961; Conkle 1973) and in Colorado (Mitton et al. 1980; Linhart 1988). On a local scale, stands on north- and south-facing slopes can consist of genetically-differentiated "aspect races" (Linhart 1988).

In addition to the large-scale geographic variability noted above, and discussed in more detail in Wang (1977), Friedman (1988), and Conkle and Critchfield (1988), there is a large amount of within-stand variation in morphology (Friedman 1988; Linhart et al. 1989), electrophoretically-detectable

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²Authors are in the Department of Biology, Box 334, University of Colorado, Boulder, Colorado 80309.

genetic polymorphism (Linhart 1988), and oleoresin chemical composition (Smith 1964; Linhart and Smith in prep.; Snyder et al. in prep.).

Traditionally, the study of genetic variation in forest trees has emphasized the roles played by physical gradients in shaping variability. Most studies have been "directional" in that they have documented the correlation between one or more tree characteristics and some factor (e.g. elevation or latitude) that affects tree biology in some predictable, linear fashion: trees from northern latitudes tend to have later dates of spring burst; trees from drier climates tend to develop larger root systems.

In the future, we need to pay closer attention to the role of biotic agents within stands. These agents are many. For example, almost 200 species of insects are reported to feed on ponderosa pine (Furniss and Carolin 1977) and there are probably more yet to be identified. These pine forests have also to contend with bacterial and fungal diseases, nematodes, dwarf-mistletoe parasites, and avian and mammalian seed, phloem and needle feeders (e.g. Fowells 1965; Baumgartner and Lotan 1988). For the sake of simplicity, we refer to this assemblage of herbivores, parasites, etc., as "dependent species." Two important facts must be recognized about dependent species: (1) each of them can generate natural selection, i.e. genetic change in forests; (2) several dependent species acting in concert can produce selection pressures in divergent directions. To elaborate, (1) natural selection occurs whenever a dependent species (a) reduces the fitness of a host individual by killing it or otherwise reducing its reproductive output, and (b) chooses individual hosts on the basis of host characteristics which have hereditary components. Forest trees and other plants have many phenotypic features which have, at least in part, some genetic basis. These include morphological features such as needle or leaf shape, thickness and pubescence, bark thickness, and physiological features including relative amounts of "attractive" compounds such as sugars and amino acids, or "repellent" compounds such as terpenes and tannins. The existence of significant genetic variability for many of these characters is documented in the plant breeding and forest genetics literatures (e.g. Allard 1960; Stern and Roche 1974; Dorman 1976; Wright 1976) and, at least for some characters, in ponderosa pine (Friedman 1988; Linhart et al. 1989). (2) Dependent species represent a variety of lifeforms, and therefore a diversity of physiological activities which can result in a diversity of host preferences. Differential host preference can generate diversifying selection. Examples of differential host utilization are reviewed in Linhart (1989) and summarized in table 1. Each of these examples documents the fact that individual trees or other plants possessing certain characteristics are attractive to a given dependent species and simultaneously less attractive to another dependent species. In other words, selection of individual host trees can be species-specific.

There are exceptions to this pattern, also discussed in Linhart (1989), as when *Leptographium* or *Arceuthobium*-infested ponderosa pine are simultaneously attractive to porcupines. However, there is much evidence to suggest that what makes a host tree attractive to e.g. a fungus, an insect, or a mammal involves specific features of host phenotype, presumably because of physiological constraints and requirements of the dependent species.

Given the large numbers of dependent species feeding upon forest trees such as ponderosa pine, the diversifying selection generated is "multi-directional," and may be at least partially responsible for the high levels of genetic variability documented in this and other tree species (Hamrick et al. 1979; Linhart 1989). When different dependent species differentially utilize specific host individuals on the basis of these hosts' genetically-determined phenotypic traits, and thereby differentially affect host fitness, diversifying selection occurs within stands. Data are still too scant to demonstrate that each of the major dependent species that damage ponderosa pine contributes to diversifying selection. To illustrate how dependent species can generate diversifying selection, we focus below on two mammals that both feed on ponderosa pine phloem.

ABERT'S SQUIRREL FEEDING PATTERNS

The tassel-eared, or Abert's squirrel (*Sciurus aberti*) is restricted to stands of ponderosa pine in Colorado, New Mexico, Arizona and Utah in the U.S., and along the Sierra Madre Occidental to southern Durango in Mexico (Diersing and Hoffmeister 1978). It is dependent upon ponderosa pine trees for food and nest sites (Keith 1965). The squirrel's diet varies seasonally with the availability of various food items, but consists almost entirely of tissues from ponderosa pine and other species which occur in close association (often symbiotically) with it. Abert's squirrel is thus considered a food-specialist.

Along the Colorado Front range, observations by M.A.S. indicate that during the summer months and continuing into autumn, the squirrels feed heavily upon the seeds of developing ovulate cones, when available, as well as upon a variety of hypogeous and epigeous fungi. The seeds of ponderosa pine are high in nutritive value, and Abert's squirrels can reduce the cone crop up to 75% (Larson and Schubert 1970). From autumn until well into spring, the diet is composed primarily of inner bark (mostly phloem) stripped from ponderosa pine twigs. In spring, staminate cones and apical buds of ponderosa pines are also important food items. These observations are generally consistent with those reported by other investigators from various parts of the squirrel's range (Keith 1965; Farentinos 1972; Stephenson 1974; Hall 1982; States et al. 1988). In Arizona, where Gambel oak (*Quercus gambelii*) is a common associate of ponderosa pine, Stephenson (1974) reported that acorns of this species, when available, can comprise up to 40% of the autumn diet. Hall (1981) refers to a number of miscellaneous (uncommon) food items, including seeds of other conifers and lupine, leaves of New Mexican locust, and mistletoe. Occasional feeding on carrion (Keith 1965) and gnawing of shed antlers (Keith 1965; Hall 1981) have also been reported.

Ponderosa pine phloem, the primary (at times sole) food item taken in winter, is of poor nutritional quality (Patton 1974) compared with other foods utilized by the squirrels. Low in protein and fat (Patton 1974), it contains appreciable quantities of monoterpenes, a group of secondary plant metabolites with deterrent effects upon a number of herbivores (Farentinos et al. 1981; Denno and McClure 1983; Reichardt et al. 1987). Phloem-feeding, always the winter mainstay of Abert's squirrels, may be especially important in years of poor cone production, when reliance upon phloem begins earlier (Goldman 1928; Bailey 1931; Keith 1965; States et al.

Table 1. Examples of differential host utilization. Intraspecific variability in a host plant is associated with interspecific differences in host preference by species of parasite or herbivore (i.e. dependent species).

Host Species	Dependent Species	Preference Pattern	References
<i>Pseudotsuga menziesii</i>	Deer (<i>Odocoileus hemionus</i>) Hare (<i>Lepus americanus</i>)	No correlation between herbivore spp. in preference for specific clones	Dimock et al. 1976
	Wooly aphid (<i>Gilletteella cooleyi</i>) Needle cast fungus (<i>Rhabdocline pseudotsugae</i>)	Populations resistant to aphid are susceptible to fungus	Stephan 1987
<i>Pinus radiata</i>	<i>O. hemionus</i> Porcupine (<i>E. dorsatum</i>)	The herbivores prefer different clones	Hood and Libby 1980
<i>Camellia sinensis</i>	80 spp. of phytophagous insects	Guilds which vary in feeding patterns prefer hosts with different leaf characters	Banerjee 1987
<i>Pinus ponderosa</i>	<i>O. hemionus</i> Rabbit (<i>Sylvilagus nuttali</i>) <i>E. dorsatum</i>	<i>O.h.</i> and <i>S.n.</i> prefer trees of same origin. <i>E.d.</i> preferences very different	Squillace and Silen 1962
	<i>O. hemionus</i> Wooly aphid (<i>Pineus coloradensis</i>)	Feeding tree distributions show no significant correlation	Linhart in prep
	Porcupine (<i>E. dorsatum</i>) Squirrel (<i>S. aberti</i>)	<i>E.d.</i> and <i>S.a.</i> feed on trees with different resin and phloem characteristics	Habeck in prep Snyder in prep
<i>Pinus contorta</i>	<i>Arceuthobium americanum</i> <i>Dendroctonus ponderosae</i>	Mistletoe-infected trees are less susceptible to beetle attack	Hawksworth and Johnson 1989

1988), and in years of heavy snow cover, when the animals may be prevented from foraging for higher-quality foods. Abert's squirrels cache very little or no food (Keith 1965), and must feed daily (Golightly and Ohmart 1978), even in inclement weather. Stephenson and Brown (1980) presented data which correlate snow cover with squirrel mortality, and suggested that prolonged reliance upon phloem might be responsible.

Apparent preferences for particular, individual trees as sources of phloem (referred to henceforth as target trees) have been noted by a number of investigators (Goldman 1928; Pearson 1950; Keith 1965; Farentinos 1972; Pederson et al. 1976; Capretta and Farentinos 1979; Hall 1981; Pederson and Welch 1985). Target trees are visually indistinguishable from nearby trees which are not utilized as sources of inner bark (non-target trees) and, along the Colorado Front Range, account for a relatively small percentage (<10%) of trees in stands which support squirrel populations. There has been considerable interest in determining the basis for this apparent selectivity. Because target trees do not differ significantly from nearby non-target trees on the basis of such characteristics as size, age, solar exposure, etc., research

efforts have concentrated largely on biochemical differences between them. Below, we summarize the biochemical work published to date.

As early as 1965, Keith (1965) suggested that Abert's squirrels may select target trees which taste better or are higher in nutritive value. Hall (1967) suspected that target tree phloem might taste sweeter, and subsequent analyses by Thomas (1979) supported this idea. Capretta and Farentinos (1979) reported that their preliminary data showed no apparent differences in sugar content between target and non-target tree phloem, but suggested that target tree phloem may contain significantly higher amounts of proteins and lower levels of monoterpene hydrocarbons. Farentinos et al. (1981) reported that twigs from target trees contained smaller amounts of monoterpenes, and that captive squirrels avoided food laced with high amounts of alpha-pinene (a monoterpene found in ponderosa pine tissues). Pederson and Welch (1985), however, found no difference between monoterpene levels in target and non-target trees, and suggested instead that squirrels prefer trees with inner bark that is easily peeled from twigs. Hall (1981) analyzed oleoresin for monoterpene

composition, and found no significant differences in amounts of individual monoterpenes between target and non-target trees.

Despite evidence that taste is more important than natural contextual cues (e.g. the presence of conspecifics, etc.) in mediating patterns of target tree utilization (Capretta et al. 1980), the biochemical bases of target tree selection have not been clearly demonstrated. Factors mediating target tree selection are currently being examined along the Colorado Front Range, and a partial summary of results is included in table 2 (Snyder in prep.).

PORCUPINE FEEDING PATTERNS

The porcupine (*Erethizon dorsatum*) ranges throughout North America, primarily in forested regions. It is a classic example of a generalist herbivore and its diet may vary dramatically from season to season and among habitats. A typical summer diet consists of herbaceous plants, tree seedlings, foliage and fruits. During the winter, porcupines usually eat inner bark, conifer needles and dwarf-mistletoe (Brander 1973; Dodge 1967; Spencer 1962; Taylor 1935; Woods 1973).

There is indirect evidence that porcupines may utilize individual trees based, in part, upon concentrations of nitrogen (Cabanac 1977; Roze 1989), phosphorus (Stricklan et al. 1983), fiber (Stricklan et al. 1983) and sodium (Roze 1989). These traits can reflect differences in physiology (e.g. rate of ion uptake from soil) which are known to have a genetic component in certain species (Allard 1960; Antonovics et al. 1971), although nothing is known about this for ponderosa pine.

Ponderosa pine phloem is a principal winter food source for porcupines in the western U.S. Within populations of ponderosa pine, porcupines often eat the phloem of some individuals repeatedly while other trees remain untouched. Many people have reported that within mixed-aged stands, target trees could be differentiated from non-target trees based upon their size class and/or vigor. Most target trees appeared to belong to the pole-sized diameter class of about 10 to 25 centimeters (4 to 10 inches) (Curtis and Wilson 1953; Van Deusen and Myers 1962; Storm 1962; Smith 1975). Young, pole-sized trees are often fast-growing and therefore contain higher levels of fats and carbohydrates than slower-growing trees (Harder 1980; Krefting et al. 1962; Shapiro 1949; Taylor 1935). It is not clear to what extent tree vigor in the stands studied is simply a function of age and resource availability; it is known to have a genetic component in ponderosa pine in certain situations (Friedman 1988; Linhart and Mitton 1985).

In contrast to other studies in ponderosa pine forests, Taylor (1935) observed the heaviest porcupine damage in dry, rocky sites where the ponderosa pines were slow-growing, small, and often had irregular growth forms. This observation may be explained by two other factors not related to the nutritive content of phloem per se: 1) the stunted trees were more heavily infested with dwarf-mistletoe (*Arceuthobium* spp.) than more vigorous trees (Taylor 1935); 2) porcupines appear to have higher population densities near rocky ridges, possibly because they find suitable den-sites in such locations.

Dwarf-mistletoe appears to be a favorite food source for porcupines. Stomach content analyses done by Taylor (1935) showed that dwarf-mistletoe was the principal food source for all porcupines (n = 57) during September, October and

November, and some individuals fed exclusively upon it throughout the winter. In some instances, porcupines have even been observed to remove the dwarf-mistletoe foliage without gnawing on the bark (Taylor 1935). Preference studies with captive porcupines have concluded that porcupines prefer dwarf-mistletoe over needles and phloem (Taylor 1935).

In eastern Oregon, Smith (1975) reported that most targeted Douglas fir trees were infected with dwarf-mistletoe. Damage was most extensive on infected branches. Smith found no correlation between dwarf-mistletoe and porcupine feeding, as Taylor (1935) had observed in Arizona. However, Lawrence (1957) claimed that infected ponderosa pine trees in eastern Oregon were preferentially fed upon by porcupines.

Besides dwarf-mistletoe, porcupines also select trees infected with *Leptographium* fungi. This root fungus clogs a tree's tissues, resulting in retention of sugar in the upper bole. Porcupines prefer infected trees even before there is any visible sign of infection (Spencer 1964). For unexplained reasons, porcupines have also been reported to preferentially feed upon lodgepole pines infected with Comandra blister rust (*Cronartium comandas*) (Mielke 1957 in Storm 1962).

Taylor's (1935) observation that target trees were growing near den-sites was also reported by others (Spencer 1964; Storm 1962). Other physical and geographical factors which may influence feeding patterns of porcupines are distance to water (Storm 1962; Speer and Dilworth 1978), proximity to summer feeding areas (Harder 1980; Van Deusen and Myers 1962), and canopy density (Taylor 1935; Curtis and Wilson 1953; Storm 1962; Smith 1979, 1982). These physical and geographical attributes may or may not be related to genetically-determined traits, although a tree's ability to survive in certain microsites may be influenced by genetic factors.

There is evidence that porcupines can consistently differentiate among phenotypes. In a study of ponderosa pine plantations in Washington and Oregon, porcupines showed a significant and repeated preference for trees from specific seed sources. The same preferences were maintained over a 32-year period and in two plantations occupying significantly different habitat types. These preferences were radically different from those of rabbits and deer, which were more similar to each other than to porcupines in their feeding patterns (Squillace and Silen 1962).

In summary, evidence for selective feeding by porcupines is scattered, and sometimes contradictory. Observations of porcupines and dwarf-mistletoe provide a glimpse of how complex the relationships among host tree, parasites, and herbivores can be. For example, it has been demonstrated that susceptibility of a tree to dwarf-mistletoe parasitism has a genetic component and that the presence of dwarf-mistletoe significantly reduces the fitness of a tree (Roth 1974). If a parasitized tree is unharmed when a porcupine consumes the dwarf-mistletoe, as has been reported (Taylor 1935), the tree's fitness may be increased. If, however, the porcupine also consumes tree tissues, as has also been observed (Lawrence 1957; Smith 1975), then the fitness of the tree may be reduced.

DIFFERENTIAL UTILIZATION OF PONDEROSA PINE PHLOEM BY ABERT'S SQUIRRELS AND PORCUPINES

As discussed above, Abert's squirrels (food specialists) and porcupines (food generalists) differ with respect to

Table 2. Differences between target and non-target trees fed upon by Abert's squirrels and by porcupines. All features are $\bar{X} \pm S.E.$. Sample sizes: for squirrels, N = 23 paired comparisons for phloem characters, and 20 paired comparisons for xylem characters, except N = 60 for xylem oleoresin flowrate values; for porcupines, N = 20 paired comparisons for phloem characters, and N = 17 paired comparisons for xylem characters. All squirrel-related tests involved trees at one site, within a relatively small area. Porcupine-related tests were done with trees at several sites, distributed over a much larger area. Analyses varied with characters compared and included ANOVA and Mann-Whitney U-tests. Levels of significance are shown for each character.

Character	Dependent Species					
	Squirrel			Porcupine		
	Target trees	Non-target trees	Signif.	Target trees	Non-target trees	Signif.
PHLOEM:						
Total nonstructural carbohydrates (%)	6.5 \pm 0.4	4.7 \pm 0.5	<.025	8.5 \pm 0.5	8.6 \pm 0.4	N.S.
Zn (ppm)	38.0 \pm 1.8	38.8 \pm 1.5	N.S.	35.4 \pm 1.1	37.2 \pm 1.15	N.S.
Ti (ppm)	1.6 \pm 0.1	1.8 \pm 0.2	N.S.	1.8 \pm 0.2	2.3 \pm 0.2	0.042
Na (ppm)	18.0 \pm 2.5	9.9 \pm 1.5	<0.01	5.9 \pm 2.9	5.8 \pm 2.7	N.S.
Si (ppm)	40.2 \pm 4.3	47.1 \pm 4.7	0.07	91.6 \pm 8.2	111.5 \pm 9.6	0.036
Hg (ppm)	0.04 \pm 0.02	0.12 \pm 0.03	<0.05	0.02 \pm 0.01	0.03 \pm 0.10	N.S.
Mg (ppm)	968.2 \pm 40.2	973.9 \pm 57.7	N.S.	1348.7 \pm 47.0	1513.4 \pm 161.4	0.011
XYLEM OLEORESIN:						
α -pinene (%)	9.3 \pm 2.3	7.4 \pm 1.2	N.S.	7.5 \pm 2.2	7.0 \pm 0.9	N.S.
β -pinene (%)	16.7 \pm 1.7	22.6 \pm 2.1	<0.05	22.5 \pm 2.7	23.1 \pm 2.0	N.S.
myrcene (%)	7.3 \pm 1.2	7.2 \pm 0.8	N.S.	7.5 \pm 0.8	6.6 \pm 0.7	N.S.
limonene (%)	2.1 \pm 0.8	3.6 \pm 0.9	<0.05	1.5 \pm 0.4	3.5 \pm 0.7	N.S.
β -phellandrene (%)	0.5 \pm 0.1	0.8 \pm 0.1	<0.01	0.9 \pm 0.1	0.8 \pm 0.1	N.S.
r-terpinene (%)	0.14 \pm 0.03	0.19 \pm 0.03	<0.05	0.2 \pm 0.04	0.2 \pm 0.02	N.S.
Flowrate (ml/24h)	2.0 \pm 0.4	5.9 \pm 0.6	<0.001	4.5 \pm 0.9	5.9 \pm 0.6	N.S.

observed patterns of host tree utilization. Below we present empirical evidence of differential host tree utilization by these two species in Arizona and Colorado.

In the Pearson Natural Area northwest of Flagstaff, Arizona, over 3300 trees were tagged and damage by several dependent species was noted periodically over a 50-year period by U.S. Forest Service personnel (Avery et al. 1976). Preliminary tabulations show evidence of different trees being selected by porcupines and squirrels. A tree was recorded as damaged if it was attacked by one of the dependent species at any time during the 50-year period. Abert's squirrels and porcupines usually fed on different trees. There were no consistent size differences between trees upon which the two species fed. Of 655 trees attacked by either animal species, only 18 were fed upon by both. If utilization by the animals were completely random, 27 trees would be expected to show damage by both. The difference is not statistically significant, however the pattern observed and our data from the Colorado Front Range suggest that 1) the animals rarely select the same target trees, and 2) those attacked by squirrels and those attacked by porcupines have different characteristics.

In the Colorado Front Range, one of us (M.A.S.) is completing six years of work on Abert's squirrel-ponderosa pine interrelationships. Porcupine feeding patterns are being investigated by S.A.H. Although the focus and scope of our work have differed, the measurement of a variety of characters was common to both our investigations, and therefore permits comparison of tree characteristics associated with feeding patterns of the two mammals. Within each study, trees which showed evidence of recent feeding were designated as target trees. For each target tree, a corresponding non-target tree was designated on the basis of a list of criteria, including size, vigor, proximity to target tree, solar exposure, slope, etc. Comparisons were made between these pairs of target and non-target trees. A partial comparison between trees fed upon by squirrels and porcupines appears in table 2.

Abert's squirrels at three Front Range sites use only a small percentage of trees (<10%) in stands which support them. As discussed in more detail below, target tree choice is apparently mediated by a number of tree characteristics, including xylem oleoresin flowrate and monoterpene composition, as well as nonstructural carbohydrate and

mineral content of the phloem (Snyder in prep.). Monoterpene composition of the oleoresin is known to have a strong genetic basis (Smith 1977), hence the squirrels appear to be feeding, at least in part, in response to genetically-determined tree characteristics. Furthermore, trees which are utilized as sources of phloem show consistently lower reproductive output than corresponding non-target trees (Snyder in prep.).

Porcupines may also act as selective agents when they preferentially feed upon trees which have high or low levels of specific elements. Although levels of elements in plants are known to be affected by soil composition, many plants have been shown to have genetically-based variation in their propensity to take up and store a variety of elements (Antonovics et al.). The negative effects of phloem-feeding upon host trees have been documented by Lawrence (1957) and others (Taylor 1935; Storm and Halverson 1967; Smith 1975).

Although feeding by Abert's squirrels was significantly affected by qualitative and quantitative oleoresin characteristics, no such pattern was seen for porcupines (table 2). Phloem of trees utilized by Abert's squirrels had significantly higher concentrations of nonstructural carbohydrates and sodium, and lower concentrations of mercury, than that of corresponding non-target trees. Trees utilized by porcupines, however, had lower concentrations of silicon, titanium and magnesium than corresponding non-target trees.

We conclude from evidence presented above that:

1. Abert's squirrels and porcupines can act as agents of natural selection in ponderosa pine forests.
2. Because of their differential feeding patterns, Abert's squirrels and porcupines can generate diversifying selection within stands.

MANAGEMENT IMPLICATIONS

Management strategies developed for ponderosa pine stands and the dependent species which inhabit them will vary with management objectives. For example, Abert's squirrels will not likely be tolerated in seed orchards, nor porcupines in young plantations. However, these are specialized circumstances over most of the species' range. Most ponderosa pine forests are too extensive, and management objectives too complex, to lead to specific recommendations relevant to all forest conditions. We suggest, however, that certain broadly-implemented strategies of the past may not be appropriate to multiple-use management goals, in light of what we are learning about the interplay between ecology and genetics in natural stands.

In 1950, a typical response to the presence of porcupines was, "effective control can be obtained by poisoning and shooting as complementary measures" (Pearson 1950). These recommendations, along with trapping, have continued to be advocated over the decades both for tree squirrels (e.g. Pearson 1950; Evans 1988) and porcupines (e.g. Knowlton and Bruce 1954; Lawrence 1957; Hoover 1971; Smith 1975; Evans 1986, 1988), despite the fact that these measures have often been ineffective, and/or harmful to other forest denizens (e.g. Cooke and Hamilton 1957; Evans 1988).

It has become evident, in fact, that unusually large "pest" populations often result from human intervention in natural

communities. For example, in many forests, high porcupine population densities have corresponded with the over-trapping of the porcupine's primary natural predator, the fisher (*Martes pennanti*) (Stone 1952; Cook and Hamilton Jr. 1957; Smith 1975; Earle and Kramm 1981). Another porcupine predator is the mountain lion, *Felis concolor*, (Maser and Rohweder 1983) and it has also been decimated in many regions. Other human activities which may increase forest pest populations include fire suppression, logging, thinning, and establishment of plantations (Stone 1952; Cook and Hamilton Jr. 1957; Lawrence 1957; Sullivan 1986).

Because dependent species attack specific trees often on the basis of host phenotype, the impact of a given dependent species upon an entire stand is likely to be mitigated by maintaining genetically-variable forests. Maintaining genetic variability may be accomplished, in part, by maintaining forests that are reasonably similar in their complexity to those which existed prior to the arrival of Euro-Americans. In this context, the feeding activities of porcupines and Abert's squirrels should not be viewed as detrimental. This is not to say that squirrels and porcupines are "good" for the trees they damage. However, ecologically complex environments are known to maintain genetic variability within populations (Hedrick et al. 1976). For this reason, we suggest that management plans for existing ponderosa pine forests take into account the importance of maintaining ecological complexity.

In the context of forest regeneration, we already know that seed sources must originate from locations as close as possible to the site to be regenerated, because of the finely-tuned adaptations to local physical conditions known for ponderosa pine (Rehfeldt 1987; Linhart 1988). In addition, the possibility of diversifying selection by a variety of dependent species, as illustrated here and in Linhart (1989), suggests that seed sources must be as variable as possible, incorporating dozens, and if possible, a hundred or more seed parents in order to produce the large diversity of phenotypes needed to cope with the large diversity of dependent species feeding on ponderosa pine.

In the context of multiple-resource management, an additional comment seems relevant. Looking for sawlogs in the thick-branched, short trees of the Central and Southern Rocky Mountains and the southwestern U.S. makes little economic sense. It is more appropriate to recognize the value of these forests as important wilderness, camping, and recreation areas. The fact that we need to make reservations for camping in some of these forests is a clue to the importance of wild areas. From this perspective, maintaining (or allowing the continued existence of) reasonable populations of wildlife is important, even if some species feed on ponderosa pine. If we were successful in eliminating all animal species that sometimes damage trees, we might have trees that grow faster and produce more wood volume and/or seeds. But such an approach would clearly be inconsistent with multiple-use management goals.

In summary, we suggest that (1) the maintenance of genetic variability which results from diversifying selection is important to the overall health of forests which are managed for multiple uses; and (2) management strategies intended to minimize the effects of phloem-feeding by Abert's squirrels and porcupines (or other species affecting tree fitness) should recognize the potentially important role of these species in generating diversifying selection within stands.

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LITERATURE CITED

- Allard, R.W. 1960. Principles of plant breeding. Wiley, New York.
- Antonovics, J., A.D. Bradshaw, and R.G. Turner. 1971. Heavy metal tolerance in plants. *Advances in Ecological Research* 7:1-85.
- Avery, C.C., F.R. Larson, and G.H. Schubert. 1976. Fifty-year records of virgin stand development in southwestern ponderosa pine. USDA Forest Service General Technical Report RM-22.
- Bailey, F.M. 1931. Mammals of New Mexico. *North American Fauna* 53:1-412.
- Banerjee, B. 1987. Can leaf aspect affect herbivory? A case study with tea. *Ecology* 68:839-843.
- Brander, R.B. 1973. Life-history notes on the porcupine in a hardwood-hemlock forest in upper Michigan. *Michigan Academy* 5:425-433.
- Cabanac, M. 1971. Physiological role of pleasure. *Science* 173:1003-1007.
- Capretta, P.J., and R.C. Farentinos. 1979. Determinants of selective herbivory in tassel-eared squirrels (*Sciurus aberti*), p. 205-218. *In* Preference behaviour and chemoreception. J.H.A. Kroeze, ed. Information Retrieval Limited, London.
- Callaham, R.Z., and A.R. Liddicoet. 1961. Altitudinal variation at 20 years in ponderosa and Jeffrey pines. *Journal of Forestry* 59:814-820.
- Capretta, P.J., R.C. Farentinos, V.M. Littlefield, and R.M. Potter. 1980. Feeding preferences of captive tassel-eared squirrels (*Sciurus aberti*) for ponderosa pine twigs. *Journal of Mammalogy* 61:734-737.
- Conkle, M.T. 1973. Growth data for 29 years from the California elevational transect study of ponderosa pine. *Forest Science* 19:31-39.
- Conkle, M.T., and W.B. Critchfield. 1988. Genetic variation and hybridization of ponderosa pine, p. 27-43. *In* D.M. Baumgartner and J.E. Lotan (eds.). Ponderosa pine: the species and its management, 281 p. Washington State University Cooperative Extension, Pullman, Wash.
- Curtis, J.D. and A.K. Wilson. 1953. Porcupine feeding on ponderosa pine in central Idaho. *Journal of Forestry* 51:339-341.
- Denno, R.F., and M.S. McClure, eds. 1983. Variable plants and herbivores in natural and managed systems. 717 p. Academic Press, New York.
- Dimock, E. J., R. R. Silen, and V. E. Allen. 1976. Genetic resistance in Douglas-fir to damage by showshoe hare and black-tailed deer. *Forest Science* 22:106-121.
- Dodge, W. E. 1967. The biology and life history of the porcupine in Western Massachusetts. Doctoral dissertation, 162 p. University of Massachusetts.
- Dorman, K.W. 1976. The genetics and breeding of southern pines. USDA Forest Service Handbook No. 471.
- Evans, J. 1988. Animal damage and its control in ponderosa pine forests, p. 105-114. *In* D.M. Baumgartner and J.E. Lotan (eds.). Ponderosa pine: the species and its management, 281 p. Washington State University Cooperative Extension, Pullman, Wash.
- Farentinos, R.C. 1972. Observations on the ecology of the tassel-eared squirrel. *Journal of Wildlife Management* 36:1234-1239.
- Farentinos, R.C., P.J. Capretta, R.E. Kepner, and V.M. Littlefield. 1981. Selective herbivory in tassel-eared squirrels: role of monoterpenes in ponderosa pines chosen as feeding trees. *Science* 213:1273-1275.
- Friedman, S.T. 1988. Genetic improvement of ponderosa pine: choosing appropriate strategies, p. 149-158. *In* D.M. Baumgartner and J.E. Lotan (eds.). Ponderosa pine: the species and its management, 281 p. Washington State University Cooperative Extension, Pullman, Wash.
- Goldman, E.A. 1928. The Kaibab or white-tailed squirrel. *Journal of Mammalogy* 9:127-129.
- Golightly, R.T., and R.D. Ohmart. 1978. Heterothermy in free-ranging Abert's squirrels (*Sciurus aberti*). *Ecology* 59:897-909.
- Hall, J.G. 1967. White tails and yellow pines. *National Parks Magazine* 41:9-11.
- Hall, J.G. 1981. A field study of the Kaibab squirrel in Grand Canyon National Park. *Wildlife Monographs* No. 75.
- Hamrick, J. L., Y. B. Linhart, and J. B. Mitton. 1979. Relationships between life history characteristics and electrophoretically-detectable genetic variation in plants. *Annual Review of Ecology and Systematics* 10: 173-200.
- Harder, L. D. 1980. Winter use of montane forests by porcupines in southwestern Alberta: preferences, density effects and temporal changes. *Canadian Journal of Zoology* 58:13-19.
- Hawksworth, F.G., and D.W. Johnson. 1989. Biology and management of dwarf-mistletoe in lodgepole pine in the Rocky Mountains. USDA Forest Service General Technical Report RM-169.
- Hedrick, P.W., M.E. Ginevan, and E.P. Ewing. 1976. Genetic polymorphism in heterogeneous environments. *Annual Review of Ecology and Systematics* 7:1-32.
- Hoffmeister, D.F., and V.E. Diersing. 1978. Review of the tassel-eared squirrels of the subgenus *Otosciurus*. *Journal of Mammalogy* 59(2):402-413.
- Hood, J. V. and W. J. Libby. 1980. A clonal study of intraspecific variability in radiata pine. I. Cold and animal damage. *Australian Forest Resources* 10:9-20.
- Keith, J.O. 1965. The Abert squirrel and its dependence on Ponderosa pine. *Ecology* 46:150-163.
- Larson, M.M., and G.H. Schubert. 1970. Cone crops of Ponderosa pine in central Arizona including the influence of Abert squirrels. U.S. Department of Agriculture Forest Research Paper RM-58, 15 p.
- Knowlton, G.F., and J.V. Bruce. 1957. Controlling porcupines. Utah State Agricultural College Extension Service Circular number 207.
- Krefting, L.W., J.L. Stoeckler, B.J. Bradle, and W.D. Fitzwater. 1962. Porcupine-timber relationships in the Lake States. *Journal of Forestry* 60:325-330.
- Lawrence, W.H. 1957. Porcupine control: a problem analysis. *Forestry Research Notes- Weyerhaeuser Timber Company, Forestry Research Center, Centralia, Wash.*
- Linhart, Y.B. 1988. Ecological and evolutionary studies of ponderosa pine in the Rocky Mountains, p. 77-89. *In* D.M. Baumgartner and J.E. Lotan (eds.). Ponderosa pine: the species and its management, 281 p. Washington State University Cooperative Extension, Pullman, Wash.

- Linhart, Y.B. 1989. Interactions between genetic and ecological patchiness in forest trees and their dependent species, p. 393-430. In J.H. Bock and Y.B. Linhart (eds.). Evolutionary ecology of plants, 600 p. Westview Press, Boulder, Colo.
- Linhart, Y.B., M.C. Grant, and P. Montazer. 1989. Experimental studies in ponderosa pine. I. Relationship between variation in proteins and morphology. American Journal of Botany 76(7):1024-1032.
- Maser, C., and R.S. Rohweder. 1983. Winter food habits of cougars from northeastern Oregon. Great Basin Naturalist 43:425-428.
- Mitton, J.B., K.B. Sturgeon, and M.L. Davis. 1980. Genetic differentiation in ponderosa pine along a steep elevational transect. Silvae Genetica 29:100-103.
- Myers, C.A. 1974. Multipurpose silviculture in ponderosa pine stands of the montane zone in central Colorado. USDA Forest Service Research Paper RM-132. Rocky Mountain Forest and Range Experiment Station, 15 p. Fort Collins, Colo.
- Patton, D.R. 1974. Estimating food consumption from twigs clipped by the Abert squirrel. USDA Forest Service Research Note RM-272, 3 p.
- Pearson, G.A. 1950. Management of Ponderosa pine in the Southwest as developed by research and experimental practice. U.S. Department of Agriculture Monograph 6, 218p.
- Pederson, J.C., R.N. Hasenyager, and A.W. Heggen. 1976. Habitat requirements of the Abert squirrel (*Sciurus aberti navajo*) on the Monticello District, Manti-LaSal National Forest of Utah. Utah Division of Wildlife Research Publication No. 76-9, Salt Lake City, Utah.
- Pederson, J.C., and B.L. Welch. 1985. Comparison of ponderosa pines (*Pinus ponderosa*) as feed and nonfeed trees for Abert squirrels (*Sciurus aberti*). Journal of Chemical Ecology 11:149-158.
- Rehfeldt, G.E. 1987. Adaptive variation and seed transfer for ponderosa pine in central Idaho. USDA Forest Service Research Note INT-373. Intermountain Forest and Range Experiment Station. Ogden, Utah.
- Reichardt, P., T. Clausen, and J. Bryant. 1987. Plant secondary metabolites as feeding deterrents to vertebrate herbivores, p. 37-42. In Proceedings, Symposium on Plant-Herbivore Interactions. USDA Forest Service General Technical Report INT-222, 179 p. Ogden, Utah.
- Roth, L.F. 1974. Resistance of ponderosa pine to dwarf-mistletoe. Silvae Genetica 23:116-119.
- Roze, U. 1989. The North American porcupine, 261 p. Smithsonian Institution Press, Washington, D.C.
- Shapiro, J. 1949. Ecological and life history notes on the porcupine in the Adirondacks. Journal of Mammalogy 30(3):247-257.
- Smith, G.W. 1975. An ecological study of the porcupine (*Erethizon dorsatum*) in the Umatilla National Forest, northeastern Oregon. M.S. Thesis, 101pp. Washington State University, Pullman, Wash.
- Smith, G.W. 1979. Movements and home range of the porcupine in northeastern Oregon. Northwest Science 53:277-282.
- Smith, G.W. 1982. Habitat use by porcupines in a ponderosa pine/Douglas fir forest in northeastern Oregon. Northwest Science 56(3):236-240.
- Smith, R.H. 1964. Variations in the monoterpene composition of ponderosa pine wood oleoresin, 17 p. USDA Forest Service Research Paper PSW-15. Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif.
- Smith, R.H. 1977. Monoterpenes of ponderosa pine xylem resin in western United States. USDA Forest Service Technical Bulletin No. 1532, 48 p.
- Spencer, D.A. 1958. Porcupine population fluxuations in past centuries revealed by dendrochronology. Doctoral Thesis, 33 p. University of Colorado, Boulder, Colo.
- Spencer, D.A. 1964. Porcupine population fluxuations in past centuries revealed by dendrochronology. Journal of Applied Ecology 1:127-149.
- Speer, R.J., and T.G. Dilworth. 1978. Porcupine winter foods and utilization in central New Brunswick. Canadian Field-Naturalist 92(3):271-274.
- Squillace, A.E., and R.R. Silen. 1962. Racial variation in ponderosa pine. American Society of Forestry, Forest Monograph 2. Washington, D.C.
- States, J.S., W.S. Gaud, W.S. Allred, and W.J. Austin. 1988. Foraging patterns of tassel-eared squirrels in selected ponderosa pine stands, p. 425-431. Symposium Proceedings, Management of Amphibians, Reptiles, and Small Mammals in North America, 458 p. USDA Forest Service General Technical Report RM-166. Fort Collins, Colo.
- Stephan, B. R. 1987. Differences in the resistance of Douglas-fir provenances to the woolly aphid *Gilletteella cooleyi*. Silvae Genetica 36:76-79.
- Stephenson, R.L. 1974. Seasonal food habits of Abert's squirrels, *Sciurus aberti*. Journal of the Arizona Academy of Science 9, Proceedings Supplement.
- Stephenson, R.L., and D.E. Brown, 1980. Snow cover as a factor influencing mortality of Abert's squirrels. Journal of Wildlife Management 44:951-955.
- Stern, K., and L. Roche. 1974. Genetics of forest ecosystems. Springer Verlag. Berlin.
- Storm, G.L. 1962. Porcupine damage in ponderosa pine stands of western Montana. Master's Thesis, 140 p. Montana State University, Bozeman, Mont.
- Storm, G.L., and C.H. Halverson. 1967. Effects of injury by porcupines on the radial growth of ponderosa pine. Journal of Forestry 65:740-743.
- Stricklan, D., J.T. Flinders, and R.G. Cates. 1986. Ecological and nutritional factors influencing porcupine winter dietary selection in the mountain brush zone of Utah. Encyclia 63:200-202. Utah Academy of Sciences, Arts and Letters.
- Sturgeon, K.B. 1979. Monoterpene variation in ponderosa pine xylem related to western pine beetle predation. Evolution 33:803-814.
- Sullivan, T.P. 1986. Impact of feeding damage by the porcupine on western hemlock-Sitka spruce forests of north-coastal British Columbia. Canadian Journal of Forest Research 16:642-647.
- Taylor, W.P. 1935. Ecology and life history of the porcupine (*Erethizon dorsatum*) as related to the forests of Arizona and the southwestern United States, 177 p. University of Arizona Biological Science Bulletin No. 3. University of Arizona, Tucson, Ariz.
- Van Deusen, J.L., and C.A. Myers. 1962. Porcupine damage in immature stands of Ponderosa pine in the Black Hills. Journal of Forestry 60:811-813.
- Thomas, G.R. 1979. The role of phloem sugars in the selection of ponderosa pine by the Kaibab squirrel. Unpublished M.A. thesis, San Francisco State University, San Francisco.
- Wang, C.W. 1977. Genetics of ponderosa pine. USDA Forest Service Research Paper WO-34.
- Woods, C.A. 1973. *Erethizon dorsatum*. Mammalian Species Account No. 29, p. 1-6. American Society of Mammalogists.
- Wright, J.W. 1976. Introduction to forest genetics. Academic Press, New York.

Problems of Maintaining a Viable Black Bear Population in a Fragmented Forest¹

Cheryl M. Mollohan and Albert L. LeCount²

Abstract.--From 1980 through 1985 the population characteristics and habitat requirements of a black bear (Ursus americanus) population were studied in both fragmented and unfragmented ponderosa pine-mixed conifer forests in north-central Arizona. Fragmentation of habitat made it difficult for animals to move between remaining habitat, increased vulnerability in and between remaining habitat, and restricted the ingress of new animals to replace individuals being lost from the population. We concluded that the population in fragmented habitat was historically fragile because of its dependence on low quality habitat, and that this quality had been further reduced through natural resource management practices that increased fragmentation. Fragmentation threatened the viability of the population by contributing to increased exploitation of adult females without compensating cub or subadult survival needed to replace them. Due to these effects bears in fragmented ponderosa pine-mixed conifer forest must be more closely monitored than in continuous habitat to assure that the viability of these populations are not lost.

INTRODUCTION

Forests throughout the world are changing dramatically due to an ever increasing human population's demand for wood products. Total forest acreage is being reduced, naturally uneven aged forests are being converted to even-aged monoculture plantations, and remaining natural forests are being fragmented into progressively smaller patches (Harris 1980).

Forest fragmentation has caused concern about its effect on wildlife (U.S. Dept. State 1982) because as timber stands become more isolated they take on characteristics of islands (Harris 1984). Movements of resident animals between

these islands becomes more difficult and requires more energy; reduced ingress and egress of new species members reduces genetic diversity and limits recolonization; and small populations become subject to over-exploitation due to increased vulnerability in and between islands of suitable habitat (Harris 1984).

These concerns have prompted wildlife biologists to examine the effects of forest fragmentation on various species of wildlife (Harris 1984, Meslow et al. 1981, Schoen et al. 1981, Robbins 1979, Thomas 1979). Bear biologist have also been examining how black bears use forests, and a great deal of information can be found on habitat use (Tracy et al. 1982)). Little information, however, is available on the effects of forest fragmentation on bears. Fragmentation can result in direct habitat loss, but also has the potential to influence movements, dispersal, survival, and the ability of a population to remain viable.

From 1980-1985 we worked on a black bear habitat and population study on a highly fragmented forest in north-central Arizona. Some of the results of this project have been reported in Mollohan et al. (1989), Mollohan (1987), and LeCount

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²Cheryl M. Mollohan is a graduate student in the School of Forestry, Northern Arizona University, Flagstaff, Arizona.

Albert L. LeCount is a research biologist for Arizona Game and Fish Department, Phoenix, Arizona.

(1987a, 1987b). However, while working on this project we were also able to observe and document some of the effects of forest fragmentation on bears. This paper describes these effects, how they relate to the problems of maintaining viable populations, and discusses problems that bear and habitat managers will face if their own forested bear habitat becomes fragmented.

This study would not have been possible without the help and enthusiasm of many volunteers and students that helped in data collection and summary. Technical assistance was provided by W. Carrel, R. Benda, and J. Wegge. This study was conducted under Fed. Aid in Wildl. Restor. Proj. W-78-R, Ariz. Game and Fish Department.

STUDY AREA

The 180 sq. mi. Leonard Canyon study area straddled the Mogollon Rim in north-central Arizona (Fig. 1). Elevations range from 4,900 to 7,800 ft. Precipitation averages 18.6 in., much of which falls as snow in the winter months. Temperature extremes usually range from just below 0F to about 93F (Sellers and Hill 1974).

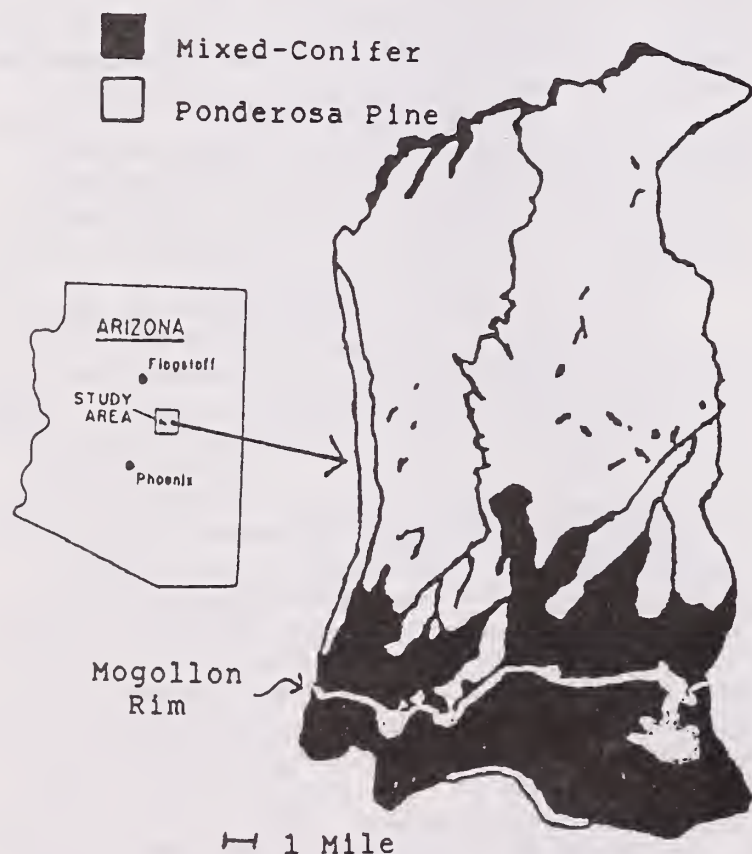


Figure 1.--Distribution of mixed-conifer and ponderosa pine vegetation on the Leonard Canyon study area, Arizona.

The Mogollon Rim is a large geologic escarpment running east to west across north-central Arizona. Topography on the 150 sq. mi. portion of the study area north of the Rim is comprised of relatively flat plateaus separated by deep canyons, and on the 30 sq. mi. area south of the Rim is made up of many steep small canyons and ridges.

This topography influenced the development of vegetation. South of the Rim more uniform soils and moisture created sites for the development of extensive stands of mixed-conifer forest. North of the Rim mixed-conifer was confined primarily to the moist canyons, and at the highest elevations along the Rim. Intervening dry ridges were covered by open ponderosa pine forest. This development fragmented the mixed-conifer vegetation into long "stringer" or "island" type blocks of habitat, with a thin band of contiguous mixed conifer near the Rim (Fig. 1).

In the late 1930's this natural fragmentation was compounded by logging. Accessible, highly economical ponderosa pine areas along ridgetops were the first to be cut, but since then almost all of the accessible ponderosa pine and mixed-conifer has been logged. By 1985 a road density of 1.9 miles of road per section had been established, and only 11% of all sections on the northern portion of the study area remained roadless (LeCount 1987b). In 1982 steep slope logging also began in the mixed conifer canyon areas. From 1982 through the conclusion of this study 15 sections on the study area had been cable logged. South of the Rim, since ponderosa pine was not abundant, little logging occurred through 1985. As a result the bear habitat remained intact and a road density of only 1.3 miles per section was established. Thirty-four percent of all sections remained completely roadless.

METHODS

Bears were captured using Aldrich foot snares and immobilized with Sernylan (phencyclidine hydrochloride). A first premolar was extracted from each captured animal and age was determined by the cementum annuli technique (Stoneberg and Jonkel 1966). Each captured bear was tagged for subsequent identification and radio transmitter collars were attached to 26 animals exceeding 1 year of age. To determine movements and home range sizes 2,120 locations were made by radio-tracking from the ground and aircraft. Home range sizes were determined by using a minimum size polygon with the area

calculated from the sum of interior triangles method (Southwood 1966).

To determine population densities north and south of the Rim, bears were divided into three age classes: cubs (< 1 year), subadults (1-3 years), and adults (> 3 years). Population size was estimated using the Leslie method (Ricker 1975) for only the adult segment of the population. The number of subadults was estimated by computing the average percent subadults captured. Details of calculations of population estimates can be found in LeCount (1987b).

Mortality of bears greater than 1 year of age was determined from radio-tracking and harvest data. Hunting seasons occurred each year on the study area but season length and techniques varied from year to year. From 1980-1982 bears could be taken from 1 September to 30 November with the use of dogs, baiting, or non-aided hunting. From 1983-1985 the season was shortened to 2 weeks in early September and the use of baits was made illegal. In all years each hunter was allowed one bear per calendar year, and was required to notify the Arizona Game and Fish Department within ten days after making a kill.

Mortality of bears less than 1 year of age was determined by radio-collaring cubs in winter dens with a mortality sensing, break-away radio-collar. Cubs were then intensively radio-tracked until they died or the animals lost their radio collars. Dens of all females accompanied by marked cubs were examined the following winter to determine cub survival through the first year of life (LeCount 1987a).

Habitat quantity was determined by using U. S. Forest Service vegetation maps to identify acres of various vegetation types on the study area. Bear use sites were classified by vegetation type or association based on Brown et al. (1979). The chi-square "goodness of fit" test (Zar 1974) was used to detect significant differences between the availability and observed use of vegetation types, site characteristics, and slopes. Preference or avoidance of each individual habitat component by collared bears was determined by applying a modified z statistic (Marcum and Laftsgaarden 1980).

Habitat quality was determined by identifying bear use microsites through intensive ground radio-tracking of radio-collared animals. After the bear was located it was left undisturbed until it departed the area. The site was then gridded for sign to verify the radio location. If fresh feeding or bedding

sign was found the site was sampled. Aspect, percent slope, logging history, topographic location and distance to nearest water were recorded. Vegetative cover and species composition were determined using a 100 foot line intercept transect. Vertical cover was determined at 3 height levels (0-1 ft., 1-6 ft., and > 6 ft.). Horizontal cover was measured using a cloth silhouette of an average size Arizona black bear and measuring the distance at which 90% of this silhouette was hidden from view. A 1/100 acre circular plot was used to obtain densities of trees and shrubs by species. The number of bear forage plants was recorded at each site, and actual food availability was also recorded by phenology ratings. Further details of habitat data analyses can be found in Mollohan (1987).

RESULTS

The Habitat

Six major vegetation types occurred on the study area; mixed-conifer, ponderosa pine, ponderosa pine-alligator juniper, maple-white fir, and grass meadow. North of the Rim ponderosa pine was the most abundant vegetation type covering 62% of the area, followed by mixed-conifer which occupied 23%, and ponderosa pine-alligator juniper with 9%. South of the Rim 96.9% of the area was covered by mixed-conifer. In this area, however, the mixed-conifer overstory contained an understory of manzanita (Arctostaphylos pringleii), emory, turbinella, and Gambel oak (Quercus emoryi, Q. turbinella, Q. Gambelii) and New Mexico locust (Robinia neomexicanus). Such a diverse understory did not occur in mixed-conifer areas north of the Rim.

Locations of radio-collared females yielded 182 bear use sites. Eighty-eight of these locations were classified as feeding sites and 57 as bedding sites. Thirty-seven contained both bedding and feeding sign. Ninety-six of all sites were occupied by females with cubs and 86 were without cubs.

Analyses of use versus availability of habitat types revealed that bears throughout the study area selected primarily for mixed-conifer, and maple areas, and against ponderosa pine. This was especially obvious north of the Rim where these 2 types made up only 23% of the vegetation but received 75% of the use (Table 1).

Total number of food species was greater south of the Rim than north due to the increased variety of mast and berry

Table 1. -- Availability of habitat types versus percent use () by portions of the Leonard Canyon, Arizona, study area, and home ranges of 2 adult female bears.

	Study Area North of Rim	Study Area South of Rim	Rose (#83)	Horton Female (#71)
Mixed-Conifer	22.6(62.7)	97.0(100.0)	22.2(64.9)	100.0(100.0)
Ponderosa Pine	62.1(10.6)	3.0(0)	68.2(16.2)	0.0(0)
Ponderosa-Alligator Juniper/Pinyon Juniper	8.8(11.9)	0.0(0)	1.7(0)	0.0(0)
Riparian	1.2(2.8)	0.0(0)	0.7(0)	0.0(0)
Grassland or Meadow	0.8(0)	0.0(0)	0.7(0)	0.0(0)
Maple	1.1(11.9)	0.0(0)	1.8(18.9)	0.0(0)
Home Range Sq. Mi.			61.6	16.1

producers in the understory, but at the time bears were found at individual feeding sites the number of food species available in any vegetation type was only 2. Cover, however, did vary between vegetation types. In mixed-conifer sites, cover between 1 and 6 ft. in height averaged 34% and horizontal visibility was 53.0 feet, and in maple 62% and 40.6 feet respectively. In contrast, ponderosa pine sites provided only 8% cover between 1 and 6 ft in height, and horizontal visibility was 93.5 feet (Mollohan et al. 1989). Bears also selected for topographical features. The study area was made up of 55% ridgetops, but only 13% of the use occurred there. In general bears selected against slopes <20% and for slopes of 20-60% (Mollohan 1987).

It appeared that bears on the study area selected habitat types on the basis of cover first and food second. Based on use of habitat types it appeared that the 62% of the area covered by ponderosa pine north of the Rim was largely unusable because of lack of cover both vegetatively and topographically. This forced bears to actually live in only about 35% of the land area. South of the Rim 97% of the land mass was usable and the habitat was not fragmented into "stringers" and "islands" as it was to the north.

Comparison of home range sizes showed that bears in fragmented habitat north of the Rim used larger areas than bears in unfragmented areas. Home range sizes for adult females in fragmented and

unfragmented habitat averaged 40.0 and 15.5 sq. mi respectively. Adult males in both areas had larger home ranges than adult females, but like females they were considerably larger in fragmented habitat. In unfragmented areas males used an average of 75.0 sq. mi. but in fragmented habitat home ranges averaged 235.0 sq. mi.

Bears in unfragmented habitat also did not make long movements within their home ranges. Their net weekly movements averaged less than 0.9 miles. Movements out of normal home ranges were also rare, and if they did occur these movements rarely exceeded 1 mile in length and all animals returned within a few days. Net weekly movements in fragmented habitat, however, averaged 2.4 miles, and all animals moved more frequently within their home range. Movements outside normal home ranges were also more frequent. Distances moved averaged approximately 10 miles, and most animals normally spent several weeks off the study area.

The Population

Over the 5 years of study 73 individual bears (45 Males, 28 Females) were captured 106 times. Forty of these animals were captured north of the Rim (29 Males, 11 Females), and 33 south of the Rim (16 Males, 17 Females). Estimated population size was 23 animals, or 1 bear/6.5 sq. mi. north of the Rim, and 21 bears, or 1 bear/1.4 sq. mi. south of the Rim. Mean age of males north of the Rim was 3.4 years, while females averaged 5.7.

South of the Rim mean ages were 5.3 and 5.6 years respectively (LeCount 1987b).

Sex ratios of adult bears did not vary significantly from the expected 50:50 ratio on either portion of the study area. However, cub and subadult ratios north of the Rim were both significantly weighted toward males ($P < 0.05$) (Table 2). The reason for the preponderance of male cubs is not known, but it appeared that the high number of subadult males resulted from an ingress of young males into an area where heavy harvest was removing many bears.

The majority of females throughout the study area had a minimum breeding age of 3.5 years. Observed mean litter size in 28 litters was 1.8 cubs. No difference in mean litter size was observed on either portion of the study area (LeCount 1987b).

Of 116 bears captured or tagged in winter dens during this study 45 (39%) died; 17 cubs, 13 subadults, 15 adults (Table 3). In addition 23 untagged bears were also taken from the study area by hunters; 2 male cubs, 8 male subadults, 7 adults (3 Males, 4 Females), and 6 bears (3 Males, 3 Females) of unknown age.

Most of the mortality throughout the study area was due to hunting (Table 3). Forty-three percent of all tagged subadults died with the majority (85%) of the loss being due to hunting. Adult mortality during the study was 35% but the highest mortality occurred north of the Rim where 55% of all tagged adults were killed. The primary cause of death north of the Rim was due to hunting, which accounted for 82% of the total mortality.

Table 2.--Sex ratios of adult, subadult, and cub black bears on the Leonard Canyon Study Area, Arizona.

Age Class	Above Rim		Below Rim	
	%Male	%Female	%Male	%Female
Adults ¹	55(11) ⁴	45(9)	48(11)	52(12)
Subadults ²	90(18) ⁵	10(2)	50(5)	50(5)
Cubs ³	72(13) ⁵	28(5)	48(10)	52(11)

¹Adults = >3 years.

²Subadults = >1 to 3 years.

³Cubs = 0 to 1 year.

⁴Number of individuals.

⁵Significant variation from 50:50 at the .05 level.

Hunting also accounted for most of the mortality below the Rim but only 13% of the total tagged adults were shot (Table 3).

DISCUSSION

Forest fragmentation has caused concern among biologist working with various species of wildlife because as fragmentation progresses remaining timber stands become isolated and begin to take on the characteristics of island ecosystems. These islands of habitat have the potential to effect wildlife by making it more difficult for individuals to move between remaining habitat, by increasing vulnerability in and between remaining habitat, and by restricting the ingress of new animals to replace individuals being lost. It appears that these concerns are all valid for bears as their habitat becomes fragmented.

Habitat Use

Forest fragmentation appeared to effect how bears used their habitat in three ways; the area they needed to make a living, their movements between usable habitat within their normal home range, and their movements to important seasonal use areas outside their normal home range.

Distribution and quantity of food has been identified as being very important in influencing black bear movements and home range sizes (Graber 1982, Amstrup and Beecham 1976, Jonkel and Cowan 1971). Lindzey and Meslow (1977), however, also identified the importance of cover to bears, and showed that the availability and juxtaposition of both food and cover contributed to overall habitat richness.

In this study cover also appeared to be important. Mixed-conifer was found to be very important to bears throughout the study area. What appeared to make this vegetation type usable was not the foods found in it, but the amount of cover it provided a bear. This vegetation type, like the unused ponderosa pine type, provided a bear an average of 2 food items while it was at the site, but horizontal cover between 1 and 6 ft. in height in this vegetation type averaged 50 feet. In ponderosa pine habitat horizontal cover averaged 94 ft. Bears were rarely located using or traveling through open ponderosa pine areas even if food was available. It is important to remember that bears were probably selecting the mixed-conifer type because of the structure of the habitat, not the species composition. Bears did not use areas of flat, open, mixed-conifer

Table 3. -- Causes of mortality of tagged cubs¹, subadults², and adults³, on the Leonard Canyon Study Area, Arizona.

	North of Rim			South of Rim			Both Areas		
	Cubs	S/adults	Adults	Cubs	S/adults	Adults	Cubs	S/adults	Adults
Total Tagged	21	20	20	22	10	23	43	30	43
Total Dying	8	8	11	9	5	4	17	13	15
Percent Dying	38	40	55	41	50	17	40	43	35
<u>Cause of Mortality</u>									
Hunting	1	7	9	0	4	3	1	11	12
Bear Predation	2	0	0	2	1	0	4	1	0
Other Predation	0	0	0	2	0	0	2	0	0
Road Kill	0	1	0	0	0	0	0	1	0
Disease	1	0	0	0	0	0	1	0	0
Capture	0	0	1	0	0	0	0	0	1
Unknown	4	0	1	5	0	1	9	0	2

¹Cubs = 0 to 1 year.

²Subadults = >1 to 3 years.

³Adults = >3 years.

that did not provide adequate cover, and in the few instances that ponderosa pine was used it always occurred on slopes >20%.

South of the Rim usable mixed-conifer habitat covered 97% of the entire area, and occurred homogeneously throughout the area. North of the Rim mixed-conifer habitat made up only 23% of the total area, and was broken up into many small blocks separated by stands of ponderosa pine. As a result bears in these fragmented areas appeared to have to use larger areas to meet their needs as evidenced by home ranges of animals in fragmented habitat averaging approximately 5 times larger than home ranges in unfragmented habitat. However, these bears did not actually have more resources available to them in these larger home ranges. If the 62% unusable ponderosa pine habitat is removed from the home range calculations the actual habitat available to males and females in

fragmented habitat averaged 87.2 and 14.8 sq. mi. respectively. These home range sizes are not significantly different ($P < .05$) from the 75.0 and 15.5 sq. mi. used by bears in unfragmented habitat.

Movements within home ranges also appeared to be influenced by fragmented habitat. Bears in fragmented areas were found to move longer distances and more frequently than those in unfragmented habitat. Two females exemplify these movements.

Female #83 (Rose), a 7.5 year old, had a 61.6 sq. mi. home range of which 26% was usable habitat (Table 1). This home range was split into many small mixed-conifer islands separated by large blocks of unusable habitat. To use this habitat Rose had to move between these small islands usually by way of connective drainages. Weekly locations made during 1982 typify these movements. During this time her weekly net movements averaged 2.3 miles per week (Fig. 2).

In contrast, bear #71 (Horton Female), a 5.5 year old female living south of the Rim had a home range of 16.1 sq. mi. that contained 100% usable unfragmented habitat (Table 1). In 1982 Horton Female moved regularly throughout her home range, but her average weekly net movements were only 0.5 miles per week (Fig. 3).

Forest fragmentation also appeared to effect bear movements to areas outside their normal home ranges. In regions with relatively homogeneous vegetation bears remain in the same areas all year and rarely make excursions outside their home ranges to find food (LeCount et al. 1984, Alt et al. 1977, Rogers 1977). Such behavior was typical of bears south of the Rim. In this area food supplies were more diverse and abundant than in areas to the north due to the variety of mast and berry producers found in the understory on this portion of the study area. In the course of 5 years of study only 4 of the 10 adult female bears inhabiting this area were observed leaving their normal home ranges, and when they did these movements normally did not exceed 1 mile in length and the animal was not out of its normal home range more than a few days.

Movements of bears to areas outside their normal home ranges in the fragmented northern portion of the study area, however, were more typical of seasonal movements observed in other areas where food availability fluctuated during the year (Graber 1982, Amstrup and Beecham 1976). This portion of the study area

contained abundant grass and forbs until mid summer when this material matured and dried, but contained only one soft and one hard mast producer (raspberry (Rubus strigosus), Gambel oak). Consequently, due to the lack of diversity of late summer and fall food producers, food availability in some years was seriously limited or non existent. During the course of this study all radio-collared bears north of the Rim made excursions to food resources south of the Rim. Fragmentation appeared to effect these movements.

Adult females began movements in late July and continued through August. The longest movement recorded was 21 miles but most were 10 miles or less. Major canyons and sidecanyons that provided both vegetative and topographic cover were used as travelways. Females moved south through these corridors and utilized seasonal areas directly south of their normal use areas. No east west movement was noted. Most females remained off the study area until September, but some did not return until shortly before denning time in November. Returns were made through the same travel corridors used to move off the study area.

Adult males also made late July and August excursions from their normal use areas but these movements were made more often and were longer than those of females. Males commonly moved 30 to 40 miles south of their normal use areas. Most used the same north-south canyon travelways used by females but several

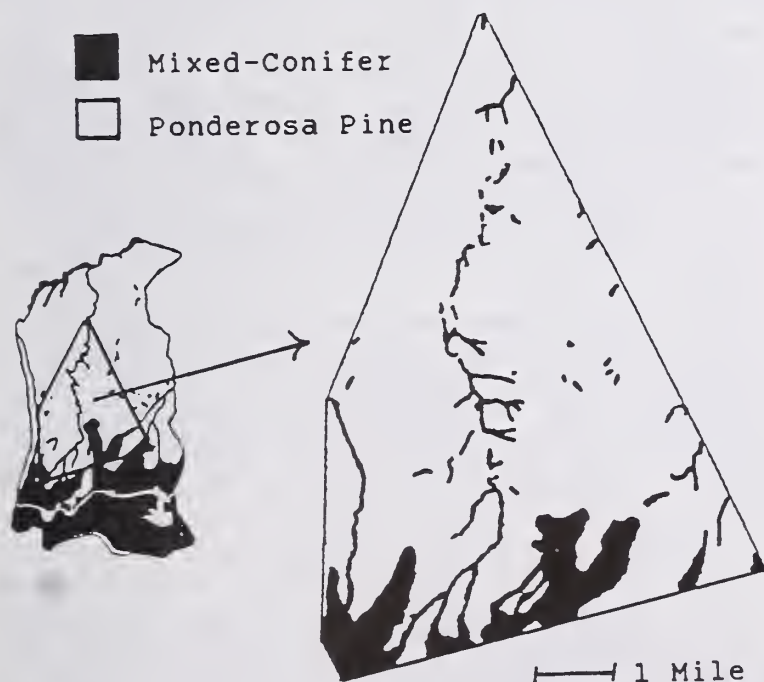


Figure 2.--Distribution of mixed-conifer and ponderosa pine vegetation in bear #83 (Rose's), 62 sq. mi. home range.

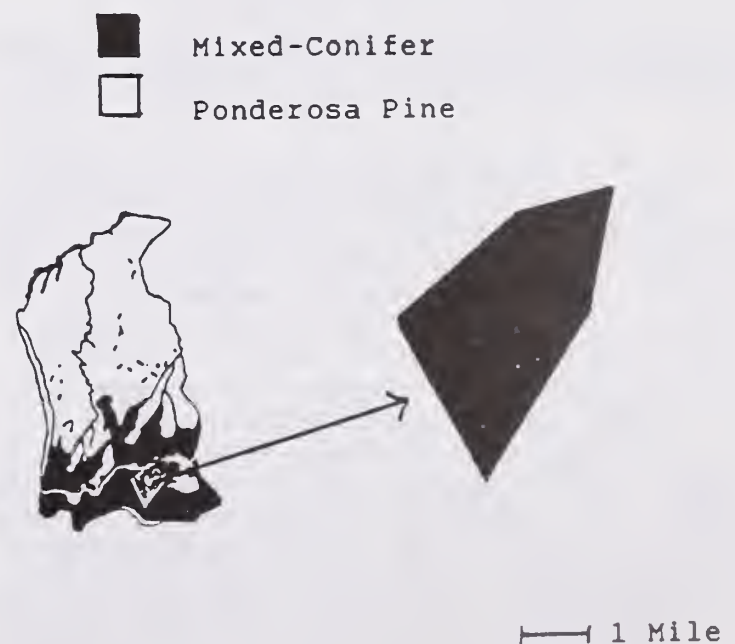


Figure 3.--Distribution of mixed-conifer and ponderosa pine vegetation in bear #71 (Horton Female's), 16 sq. mi. home range.

traveled east and west through small islands of fragmented habitat. Like females, males returned to their normal use areas on the study area to den by the same travel corridors.

Population Regulation

Habitat quality appears to be the ultimate factor in controlling black bear numbers but other factors such as nutrition, cub survival, subadult dispersal, habitat deterioration, and hunting can all be proximate regulating mechanisms (Kolenosky 1986, Hugie 1982, LeCount 1982, Young and Ruff 1982, Beecham 1980, Lindzey and Meslow 1977, Rogers 1977). In this study it appeared that increased vulnerability of adults and lack of replacement of individuals lost were the most important. Both of these problems were effected by forest fragmentation.

As forests become fragmented bears become more vulnerable to hunting because they are concentrated into smaller areas, and, if this fragmentation is created by logging the resulting road system also provides increased hunter access into bear habitat. The northern portion of the study area evolved in a naturally fragmented condition but intensive logging, especially during the 1970's and 80's compounded the problem.

This intensive logging benefited hunters. Road access was greatly increased, and bears were forced to either spend more time in smaller islands of habitat, or make more frequent moves between islands. The results of this increased fragmentation were that hunters became much more efficient at killing bears.

Of 61 bears marked north of the Rim, 17 (28%) were killed by hunters. This is in contrast to south of the Rim where only 7 of 55 (13%) were taken (Table 3). Adult females were particularly impacted in fragmented habitat. Of 9 adult females tagged during the study only 2 remained alive at the end. Hunters accounted for 5 of 7 (71%) of the mortalities. In unfragmented habitat only 1 of 12 (17%) tagged adult females were taken by hunters (Table 3.). Both of these harvest levels are much higher than on an unfragmented central Arizona study area where only 1 of 19 (5%) tagged females was harvested in an area where road densities were 0.2 miles per section (LeCount 1982). Based on our observations hunter density was similar on all three areas.

This high loss of adult females in fragmented habitat reduced the overall

reproductive capacity of the population. The high harvest rate, combined with natural mortality of adult females, resulted in a 78% reduction in the number of breeding females in the population. This loss of females reduced the maximum cub production from an average of 9 cubs per year to 2. This cub production might have been adequate to maintain the population if all cubs survived to adulthood but unfortunately this was not the case.

Of 21 cubs tagged on the fragmented portion of the study area 8 (38%) died (Table 3). This cub mortality rate was not significantly different from that found in unfragmented habitat, and although higher than in other states (Alt 1982, Jonkel and Cowan 1971) appears to be typical for Arizona (LeCount 1984). Survival beyond the first year of life, however, was poorer in fragmented habitat. Of 20 tagged subadults 7 (35%) died. All were taken by hunters (Table 3). Subadult females, like their adult counterparts, were severely impacted by hunting. During the entire study only 2 subadult females were captured in the entire 150 sq. mi. area north of the Rim, and both of these were killed before they reached breeding age. This is in contrast to the adjacent unfragmented habitat south of the Rim where 5 subadult females were captured and only 1 was killed.

This low cub and subadult survival, especially in the female segment of the population, appeared to be making it very difficult for the population in fragmented habitat to remain viable. A number of adult females were being taken each year but during the course of the study not one new female was known to be added to the population. This alone would be enough to restrict the viability of the population. However, this problem is compounded by the fact that subadult females rarely disperse from the area they were born in. While young males leave their area of birth after family breakup subadult females normally remain in their mother's home range until they become adults. As adults they often occupy adjacent home ranges to their mothers (Rogers 1977). Therefore, the only way to replace females being killed is for them to be produced by the adult females surviving on the study area.

CONCLUSION

Forest fragmentation tends to create small "islands" of usable habitat in a "sea" of unusable habitat. Movements of resident animals between these islands becomes more difficult, ingress and egress of new species members is limited, small populations become subject to over-

exploitation, and in some cases extirpation occurs (Harris 1984). This appears to be what is happening to one of our northern Arizona bear populations.

Analyses of habitat data showed that bears were primarily limited to mixed-conifer, vegetation associations because of the lack of cover and topography in other vegetation types. Virtually all of the habitat south of the Rim was made up of these associations and was usable to bears on a year round basis because it was not fragmented or isolated from other bear habitat. This habitat supported a density of 1 bear/1.4 sq. mi.

Terrain in this area was also steep and road densities low. As a result hunter access was poor, and during the 5 years of study hunters killed only 4 of 10 (40%) subadults tagged, and 3 of 23 (13%) tagged adults. Of these 7 individuals only 2 (1 adult, 1 subadult) were females. As a result of this light hunting pressure the age structure of the population was characteristic of a lightly hunted population with 70% of the bears being breeding age animals (LeCount 1982, Beecham 1980). This high number of breeding age animals appeared to allow for adequate reproduction to replace animals lost to both natural causes and to hunting, and unless harvest levels increase this population should remain stable.

North of the Rim the situation was much different. Usable habitat in this area was fragmented into small "islands" and "stringers" separated by large expanses of unusable ponderosa pine. Only 28% of the entire 150 sq. mi. area appeared to be usable for bears. This vast amount of unusable habitat in each animals home range caused home ranges sizes to be an average of 5 times greater than home range sizes for bears in unfragmented habitat, and as a result the population density averaged only 1 bear/6.5 sq. mi.

Terrain north of the Rim was relatively flat and had abundant roads. Good road access, coupled with fragmented habitat which limited bears to certain areas within their home ranges, or caused them to move through areas where they were more vulnerable, resulted in heavy hunter harvest. During the 5 years of study hunters harvested 7 of 20 (35%) tagged subadults and 9 of 20 (45%) adults. This harvest rate of adults and subadults is higher than other areas considered heavily hunted, and the 50% subadults found in the population is indicative of a highly exploited population (Kolenosky 1986, Young and Ruff 1982, Beecham 1980).

Even more important than the effect of heavy hunting on the population as a whole, however, was its effect on the female segment of the population. During the 5 years of study only 2 females died from non-hunting causes but 4 untagged and 5 of 9 tagged breeding age females were shot. During this same time period capture data, and monitoring of tagged subadult females, indicated that no new breeding females were added to the population. Undoubtedly all breeding females on the study area were not captured, but the frequency at which tagged females were recaptured indicated that this number had to be low. Therefore, the continued presence of breeding age females in fragmented habitat appeared to be seriously threatened. The 2 remaining females were growing older, and if not killed by hunters would eventually die of "old age." No new breeding age females were being added to the population because young females seldom disperse and a high percentage of the few female cubs that were being born on the area were being killed before they reached breeding age.

This naturally fragmented habitat has never, and will never be capable of supporting high bear densities, and its potential has been further limited by logging and related land use activities. As a result even if this population is rehabilitated over time it will never be able to withstand much pressure either from hunting or additional loss of habitat.

MANAGEMENT IMPLICATIONS

In fragmented habitats strong consideration must be given to preventing further fragmentation, and bear populations in such areas must be considered as very fragile and managed accordingly. Failure to consider both population and habitat management of bears in fragmented forests will inevitably lead to the decline, or even the loss, of the species in these areas.

Having an opportunity to observe bears in an area that contained both fragmented and unfragmented habitat allowed us to observe some of the changes that take place as fragmentation occurs. We believe strongly that habitat prone to fragmentation should be managed from the perspective of preventing, or halting fragmentation. Important management implications that bear and habitat managers should be aware of and consider, especially if land use practices are causing bear habitat in their area to become fragmented include:

First, as fragmentation occurs managers will have to increase their estimates of home range size and decrease estimates of population density. Fragmentation causes bears to travel over larger land areas to meet habitat needs which makes average home ranges larger, and loss of habitat due to removal of protective cover or food supplies in intervening areas decreases the total number of bears an area can support. This reduction in bear numbers will continue until unusable habitat regenerates to the point where it again adds to the total amount of usable habitat.

Second, fragmentation makes it difficult for bears to reach important seasonal food supplies. Travelways are eliminated and remaining travelways become increasingly important. As fragmentation occurs managers must make sure that isolated islands of habitat are kept to a minimum and that adequate travelways are provided between usable blocks of vegetation. If these steps are not taken bears will have greater difficulty moving to important food supplies and could become isolated from other usable habitat.

Third, forest fragmentation also increases bear vulnerability by concentrating bears and increasing hunter access. As an area become fragmented managers should anticipate that hunters will become more efficient and harvest will increase. To protect populations from overharvest managers must decrease their bear harvest by limiting more efficient hunting techniques or reducing the time hunters can be in the field. Also, since population densities will decrease as available habitat is reduced overall harvest will have to be lower than pre-fragmentation harvest to assure that overharvest does not occur.

Finally, bear populations in fragmented areas should be monitored very closely. Fragmentation not only has the potential to increase the number of bears harvested, but this increased mortality and the fragmentation itself can make it more difficult to replace animals being removed. If managers observe high numbers of females being harvested they can anticipate that reproductive potential will decline because fewer breeding age females will remain in the population. Also, as more bears are concentrated into remaining islands of habitat the potential for cubs to be found and killed by other bears, and for hunters to kill subadult females, is increased. This loss of replacement females, combined with the fact that subadult females rarely disperse, limits recruitment of new females into the population. Without new

females being added a viable breeding population can be eliminated even though male bears still remain in the area.

LITERATURE CITED

- Alt, G.L., G. J. Matula, Jr., F. W. Alt, and J. S. Lindzey. 1977. Dynamics of home range and movements of adult black bears in north-eastern Pennsylvania. Pages 131-136 in C. J. Martinka and K. L. McArthur, (eds.) Bears - their biology and management. Bear Biol. Assoc. Conf. Ser. 3.
- . 1982. Reproductive biology of Pennsylvania's black bear. Penn. Game News 53:9-15.
- Amstrup, S. C. and J. J. Beecham. 1976. Activity patterns of radio-collared black bears in Idaho. J. Wildl. Manage. 40:340-348.
- Beecham, J. J. 1980. Population characteristics, denning, and growth patterns of black bears in Idaho. Ph.D. Thesis, Univ. Mont., Missoula. 101pp.
- Brown, D. E., C. H. Low, and C. P. Pase. 1979. A digitized classification system for the southwest. J. of the Az.-Nev. Acad. Sci., Vol 14. Supp. 1. 16pp.
- Graber, D. C. 1982. Ecology and management of black bears in Yosemite National Park. Coop. National Parks Res. Study Unit, Tech. Rpt. No. 5. 205pp.
- Harris L. D. 1980. Forest and wildlife dynamics in the southeast. Trans. North Am. wildl. Nat Resour. Conf. 45:307-322.
- . 1984. The fragmented forest. The Univ. of Chicago Press, Chicago. 211pp.
- Hugie, R. O. 1982. Black bear ecology and management in the northern conifer-deciduous forests of Maine. Ph.D. Thesis, Univ. Mont., Missoula. 203pp.
- Jonkel, C. J., and I. M. Cowen. 1971. The black bear in the spruce-fir forest. J. Wildl. Manage. Mono. #27. 57pp.
- Kolenosky, G. B. 1986. The effects of hunting on an Ontario black bear population. Pages 45-56 in P. Zager (ed.). Bears their biology and management. Bear Biol. Assoc. Conf. Ser. 5.
- LeCount, A. L. 1982. Characteristics of a central Arizona black bear population. J. Wildl. Manage. 46:861-868.
- . 1984. Black bear cub production and survival in central Arizona. Ariz. Game and Fish Dept. Fed. Aid in Wildl. Restor., Final Rep., Proj. W-78-R. Phx. 10pp.

- _____. 1987a. Causes of black bear cub mortality. Pages 75-84 in P. Zager. (ed.). Bears-their biology and management. Bear Biol. Assoc. Conf. Ser 6.
- _____. 1987b. Characteristics of a northern Arizona black bear population. Ariz. Game and Fish Dept. Final Rep. F. A. Proj. W-78-R, Work Plan 2, Job 22. Ariz. Game & Fish Dept., Phx. 26pp.
- _____, R. H. Smith, and J. R. Wegge. 1984. Black bear habitat requirements in central Arizona. Ariz. Game and Fish Dept. Spc. Rpt. 14. 49pp.
- Lindzey, F. G., and E. C. Meslow. 1977. Home range and habitat use by black bears in southwestern Washington. J. Wildl. Manage. 41:413-425.
- Marcum, C. L., and D. O. Loftsgaarden. 1980. A nonmapping technique for studying habitat preferences. J. Wildl. Manage. 44:964-968.
- Meslow, E. C., C. Maser, and J. Verner. 1981. Old-growth forests as wildlife habitat. Trans. North Am. Wildl. Nat. Resourc. Conf. 46:329-344.
- Mollohan, C. M. 1987. Black bear habitat use in northern Arizona. Final Rep. F. A. Proj. W-78-R, Work Plan 4, Job 19, Ariz. Game & Fish Dept., Phx. 37pp.
- _____, W. W. Brady, and A. L. LeCount. 1989. Habitat use of an Arizona ponderosa pine-mixed conifer forest by female black bears. West. J. Appl. For. 4:6-10.
- Ricker, W. W. 1975. Computation and interpretation of biological statistics of fish populations. Bull. 191 Dept. of the Environment, Fisheries and Marine Service, Ottawa. pp 149-153.
- Robbins, C. S. 1979. Effect of forest fragmentation on bird communities. Pages 198-212 in R. M. DeGraaf and K. E. Evans (eds). Management of north central and northeastern forests for non-game birds. Proc. Workshop. U.S.D.A. For. Serv. Gen. Tech. Rep. NC-51.
- Rogers, L. L. 1977. Social relationships, movements, and population dynamics of black bears in northeastern Minnesota. Ph.D. Thesis, Univ. Minn. Minneapolis. 194pp.
- Schoen, J. W., O. C. Wallmo, and M. D. Kirchhoff. 1981. Wildlife-forest relationships: Is a re-evaluation of old-growth necessary? Trans. North Am. Wild. Nat. Resourc. Conf. 46:531-544.
- Sellers, W. D. and R. H. Hill, (eds). 1974. Arizona climate (1931-1972). The Univ. of Ariz. Press, Tucson. 616pp.
- Southwood, T. R. E. 1966. Ecological methods with particular reference to the study of insect populations. Methven and Co. Ltd., London. 524pp.
- Stoneberg, R. P., and C. J. Jonkel. 1966. Age determination of black bears by cementum layers. J. Wildl. Manage. 30:411-414.
- Thomas, J. W., (ed). 1979. Wildlife habitats in managed forests, the Blue Mountains of Oregon and Washington. U.S.D.A. For. Serv. Agric. Handb. 553. Washington, DC. 512pp.
- Tracy, D. M., F. C. Dean, C. M. Anderson, and T. M. Jordan. 1982. Black bear bibliography. Alaska Coop. Par. Study Unit, Univ. of Alaska, Fairbanks AK.
- U.S. Department of State. 1982. Proceedings of the U.S. strategy conference on biological diversity. Dept. State Publ. 9262 Intl. Organiz. and Conf. Series 300. Washington, D.C. U.S. Gov. Printing Off.
- Young, D. F., and R. L. Ruff. 1982. Population dynamics and movements of black bears in east-central Alberta. J. Wildl. Manage. 46:845-860.
- Zar, J. H. 1974. Biostatistical analysis. Prentice-Hall Inc. Englewood Cliffs, N.J. 620p.

Effects of Timber Management Practices on Elk¹

Richard L. Brown²

Elk were radio tracked to mid-day bedsites and standard overstory measurements that reflect thermal cover characteristics were taken. Sixty-four sites were located and measured in the ponderosa pine type. These have been described quantitatively and an attempt has been made to relate this information to the parameters currently used in the R03WILD modeling process.

INTRODUCTION

The accepted standard for optimum quality elk habitat calls for maintaining 60% of the total land mass in forage areas and 40% in cover areas (Black et al. 1976; and Thomas et al. 1979). Forage areas are defined as those that do not qualify as cover areas. Cover is divided into two types, hiding and thermal. Hiding cover provides an escape or security function and is defined as vegetation that will hide 90% of a standing adult elk at 200 feet or less (Thomas et al. 1979). Thermal cover protects from incoming solar radiation during warm periods and reduces the animals own radiation heat loss during cold periods. The 40/60 cover/forage ratio calls for 1/2 of the 40% to exist in the form of hiding cover, 1/4 in thermal cover and the remaining 1/4 in either hiding or thermal, whichever is the more limited.

The accepted description of habitat that provides summer thermal cover is "any stand of coniferous trees 40 feet or more in height with an average canopy closure of 70%" (Thomas et al. 1979). This definition was developed in the mixed conifer forests of Washington and Oregon. A large majority of Arizona's elk in the western half of the states range, and a much smaller percentage of those in the eastern half, summer in ponderosa pine forests. Pure ponderosa pine stands greater than 40 feet in height, rarely achieve the required 70% canopy closure. This suggests that a significant portion of Arizona's elk are using a totally different tree stand structure for this purpose. Additionally, a smaller percentage of Arizona's elk summer in Pinyon/Juniper woodland. The importance

of adequate summer thermal cover is related to maintaining a high level of reproduction. (For a more detailed discussion and associated references see Brown 1987, pages 4 and 5).

The USDA Forest Service Region III is currently implementing new multi-resource stand management prescriptions for all National Forests within Arizona. In general, forests will be managed in 10,000 acre blocks (range 8,000-12,000) comprised of 10-100 acre even aged stands, except for the old growth component which will exist in 100-300 acre stands. The 40/60 cover/forage ratio will be used as a guideline. A series of multivariate habitat models will predict probable outcomes and track results of timber harvesting operations. The R03WILD habitat capability model for elk is based on tree structural stages as well as canopy closures. It is therefore necessary, not only to identify what elk are using and describe it, but also to relate this information to the structural stage matrices used by the computer models that will direct this intensive management program.

STUDY AREA

Ponderosa Forest

Since the outset of the 1987 field season the study has been conducted within a 12 by 16 mile parcel of land just southeast of Flagstaff, Arizona. The general area extends east from Munds Park and Mountainaire to Forest Highway 3 (which connects Mormon Lake and Happy-Jack); and south from Lake Mary to Lee Butte (approximately 3 miles north of Stoneman Lake). With the exception of Mormon Mountain which supports a mixed conifer type, the area is a ponderosa pine (*Pinus ponderosa*) forest with a substantial inclusion of gambel oak (*Quercus gambelii*), and occupies an elevational range of approximately 6600 to 7700 feet. During a 1986 pilot study seven observations were obtained in areas outside the one just described. These are similar in elevation and vegetative type, and the observations have been included in our data set.

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²Richard Brown is a Research Biologist, Arizona Game and Fish Department, Flagstaff, Arizona.

All areas are producing annual calf crops in excess of 50 calves/100 cows.

Pinyon Pine/Juniper Woodland

In 1986, six observations were obtained in a P/J Woodland about nine miles northeast of Blue Ridge, Arizona and east of Highway 87. This general area will be used again during the 1989 and 1990 field seasons. It occupies an elevational range of approximately 6400 to 6800 feet and supports Utah juniper (*Juniperus osterosperma*), one seed juniper (*J. monosperma*), alligator juniper (*J. deppeana*), pinyon pine (*P. edulis*) and a small inclusion of ponderosa pine (*P. ponderosa*).

METHODS

During the months of June-August radio marked elk were located at mid-day bedsites between the hours of 10:30 AM and 3:30 PM. Only direct visual observations of animals in a bedded state, or just leaving a bed, were used as a basis for taking measurements. With the exception of cow/calf associations, in which case both sites were marked, only one bedsite per group of animals was used. The bedsite of the radio equipped animal was marked if the elk could be located. If not, the first animal seen was chosen. Estimates of select weather parameters, slope exposure and distance to roads, water and developments were made. The center of the bed impression was used to establish the center of a 16.7 ft. radius circular plot (1/50 acre). The following characteristics were measured for each tree within the plot: Stem diameter (drc for junipers, dbh for other species), height, crown ratio and crown class. Seedlings were initially counted in total. The point centered quarter method of estimating density was later substituted for the total seedling stem count (Cottom and Curtis 1956). A 5.27 foot radius plot (1/500 acre) was nested within the larger plot. This plot encompassed what the animal was bedding on or immediately next to. Within this plot, ocular estimates were made of percent ground coverage by dead and down material and rock.

Canopy closure was measured from the center of the bedsite by means of a concave spherical densimeter held at elbow height. Additionally each bedsite was evaluated for qualification as hiding cover (90% or greater level of visual obstruction at 200 feet or less) by means of an alternately red and white colored sight target (tube) two feet wide and six feet tall (Leckenby et al. 1985). The sight tube was suspended directly

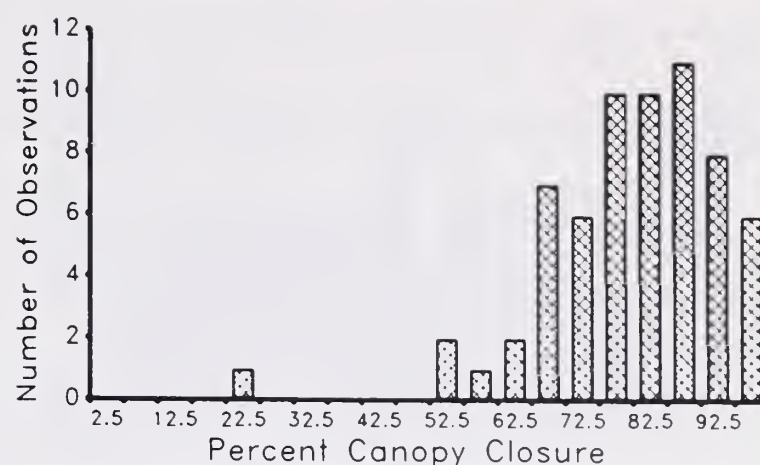


Figure 1. Frequency distribution of Ponderosa pine bedsites within canopy closure classes.

over the bedsite. Readings were taken from each of the four cardinal compass directions and averaged into a single value for the site.

A satellite plot was located 300 yards distant from the bedsite in each of the four cardinal compass directions. Data collection procedures were identical to the bedsite plot except that no sight tube data were collected. The satellite plots were used to demonstrate habitat availability and establish whether elk exhibited selectivity for certain site characteristics.

RESULTS AND DISCUSSION

Ponderosa Forest

Thermal Cover. Canopy closures on the 64 bedsites located through August of 1988 were significantly higher than those on the satellite plots ($p \leq 0.001$). The mean canopy closure of all bedsites was 82% as compared with 42% for all satellite plots. Ninety-one percent of mid-day bedsites occurred within the range of 65-100% (Figure 1). Only 25% of the satellite plots had canopy closures $\geq 65\%$ (Figure 2). This demonstrates selection for higher canopy closure.

Elk summer thermal cover is, therefore, described by examining bedsites that possessed a canopy closure of $\geq 65\%$. The few remaining observations ($< 65\%$) are believed to be outliers and are not adequate thermal cover. Average stem diameter was calculated for each of these bedsites. Individual bedsite values were then placed in stem diameter classes compatible with those used by the U.S. Forest Service in the development of the structural stage matrices for the R03WILD model (Byford et al. 1984). Within each diameter class, a mean and range (mean \pm 1 Std. Dev.) was calculated for each structural characteristic

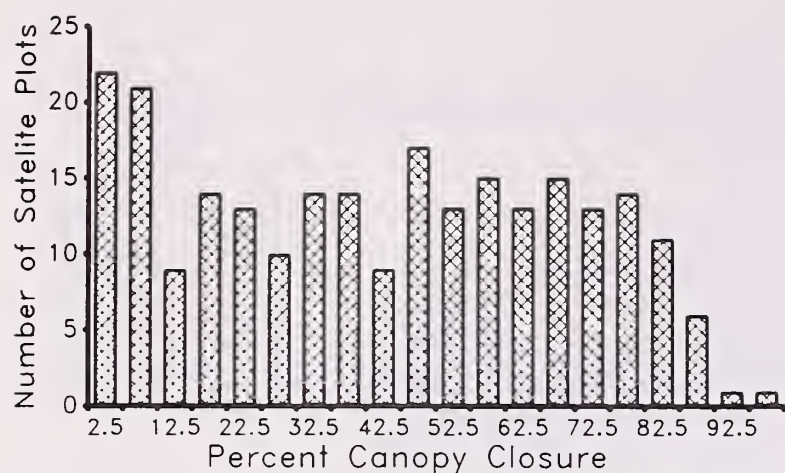


Figure 2. Frequency distribution of Ponderosa pine satellite plots within canopy closure classes.

(Table 1). In order to compare our observations with the ROWILD model, data from Table 1 were transformed and superimposed onto the USFS table of ponderosa pine structural stages (Table 2), as presented in the Wildlife Coefficients Technical Report (USFS 1984). This report recognizes the following structural stages.

Structural Stage	Description
1	Grass/Forb
2	Seedling/Sapling
	Immature
3a	10-40% canopy closure
3b	41-70% canopy closure
3c	71 + % canopy closure
	Mature
4a	10-40% canopy closure
4b	41-70% canopy closure
4c	71+ % canopy closure
5	Old Growth

The shaded areas in Table 2 indicate which structural stages are capable of providing summer thermal cover. The upper and lower boundaries of the shaded area were determined solely on the basis of stems/acre (mean + 1 Std. Dev.) within each diameter class (Table 1). No consideration was given to the structural stage classifications 1-5 or a-c. Since the data we used are only from sites with canopy closures $\geq 65\%$, the shaded area should completely cover all "c" classifications and encroach into the "b" classification. About 16% of the "b" classifications should be included because the lower limit was designated at 65% instead of 71%. In all diameter classes our data overlay has

Table 1. Mean values of measures taken at mid-day bedsites with canopy closure $> 65\%$, and occurring in Ponderosa pine forest (mean + 1 S.D.).

Diameter Class (in)	Stems Per Acre	Basal Area	SDI	Height	Canopy Closure	No. Bedsites
1.0-4.9	1306.3 (797-1816)	174.9 (123-226)	419.8 (298-542)	17.4 (13-22)	85 (76-94)	n=16
5.0-6.9	703.3 (455-952)	204.7 (143-267)	423.3 (297-550)	29.3 (23-36)	83 (75-92)	n=15
7.0-8.9	452.8 (275-631)	199.7 (112-288)	380.9 (219-543)	29.7 (22-38)	78 (68-87)	n=18
9.0-10.9	300.0 (192-408)	171.9 (107-237)	311.7 (197-427)	32.9 (23-43)	87 (79-94)	n=4
11.0-12.9	250 (179-321)	247.0 (149-345)	402.5 (252-553)	39.3 (30-49)	81 (77-85)	n=2
13.0-16.9						n=0
17.0-19.9	100 (100-100)	186.5 (148-225)	267.7 (223-312)	36.0 (31-41)	85 (68-100)	n=2
20.0-27.9						n=0
28.0+	50 (50-50)	226.2 (226-226)	273.1 (273-273)	78.0 (78-78)	73 (73-73)	n=1

missed the lower extremities of the structural stage "c"; and in the 5-7 and 7-9 inch diameter classes, has encroached into the "b" stage by about 50%. This lack of alignment between our data and the designated b and c classification used by the Forest Service is probably unimportant. Greg Goodwin (USFS Biologist, pers. comm.) has indicated that the canopy closure classifications were assigned to the crosswalk table on a best estimate basis and may themselves be slightly out of position.

The R03WILD model uses the previously discussed structural stages to predict wildlife habitat capability. Furthermore, the R03WILD elk matrix for ponderosa

Table 2. USFS structural stages used by elk for mid-day bedsites. Table from Wildlife Coefficients Technical Report (1984).

Stems Per Acre	Ponderosa Pine Diameter Classes									
	0-1	1-5	5-7	7-9	9-11	11-13	13-17	17-20	20-28	28+
1-10	1	1	1	1	1	1	1	1	5	5
11-20	1	1	1	1	1	1	4a	4a	5	5
21-40	1	1	1	1	3a	4a	4a	4b	5	5
41-80	1	1	3a	3a	3a	4a	4b	4c	5	5
81-120	1	2	3a	3a	3b	4b	4b	4c	4c	
121-200	1	2	3a	3b	3b	4b	4c	4c		
201-350	2	2	3b	3b	3c	4c	4c			
351-500	2	2	3b	3b	3c	4c				
501-700	2	2	3b	3c						
701-1000	2	2	3c							
1001-2000	2	2	3c							
2000+	2	2								

Shaded area: Stems/Acre (mean + 1 std. dev.) from elk bedsites in Table 1

Table 3. R03WILD matrix of habitat capability values for elk (USFS 1984).

Ecosystem: Ponderosa Pine

Season of Use: Year-round

Type of Use	Structural Stages								
	1	2	3a	3b	3c	4a	4b	4c	5
Feeding	1	1	1	2		2	5		2
Cover			5	2	1	5	2	1	2

pine (Table 3) shows habitat ratings for cover in all structural stages from 3a-4c and 5. Our data, to date, show elk to use structural stages 2 through 5, but not using the "a" class. The "b" class is also not used below 50% canopy closure. Each structural stage is assigned a 1-5 rating designed to reflect its value as both a feeding area and a cover area. A rating of 1 represents a full acre value of optimum habitat and a 5 represents a 1/5 acre value of the same. Data from this study do not support the R03WILD capability ratings (Table 3).

The current capability ratings could be revised by the following method. There appear to be three breaks in the Figure 1 canopy closure data that would yield functional classes similar to those in the model ("a", "b", "c"). These occur in levels of elk use (no. of elk bedsites) at the 75, 65 and 50% levels of canopy closure. Table 4 gives the frequencies of occurrence for both bedsite plots and satellite plots. Seventy percent of the bedsites occurred at canopy closure levels $\geq 75\%$; 90% at closure levels $\geq 65\%$; and 98% at closure levels $\geq 50\%$. For each of these three categories a ratio was created for the percent of the total observations in the bedsite population to the

Table 4. Frequency of occurrence of bedsites and satellite plots within canopy closure classes.

% Canopy Closure	No. Bedsites	No. Satellite Plots	% Canopy Closure	No. Bedsites	No. Satellite Plots
0-5	0	22	50-55	2	13
5-10	0	21	55-60	1	15
10-15	0	9	60-65	2	13
15-20	0	14	65-70	7	15
20-25	1	13	70-75	6	13
25-30	0	10	75-80	10	14
30-35	0	14	80-85	10	11
35-40	0	14	85-90	11	6
40-45	0	9	90-95	8	1
45-50	0	17	95-100	6	1
			n=64	n=245	

Table 5. Ratios of percent use of bedsites to habitat availability (satellite plots).

%Canopy Closure	%Bedsite Plots/Satellite Plots
75-100	70/13=5.4
65-74	20/11=1.8
50-64	8/17=0.47

percent of total observations in the satellite population (Table 5). The ratio relates frequency of use to availability. The quotients clearly demonstrate declining elk use as canopy closure decreases, and suggest that Relative Habitat Capability Ratings of 1, 3 and 11 might be appropriate for 75-100, 65-74 and 50-64% canopy closure ranges in the R03WILD matrix. These values were obtained by dividing each of the three quotients into the first. There is nothing in our current data base to suggest that canopy closures $< 50\%$ provide any useful level of thermal cover. However, one addition to the matrix is made. Structural stage 2 is apparently capable of producing high quality thermal cover. At least 14 of the 16 observations in the Table 1 data for the 1.0-4.9 diameter class had canopy closure levels $\geq 75\%$.

The study plan calls for analysis of stem density and diameter data in an attempt to identify elk thermal cover without the use of direct canopy closure estimates. An amendment to the new Forest Plan for the Coconino attempts to define thermal cover in terms of either growing stock level or basal area within diameter classes. McTague and Patton (1989) have suggested that Stand Density Index values might provide a more precise description than basal area. Upon obtaining a complete data set, we will examine any relationships that might exist.

Hiding Cover. The R03WILD matrices treat cover as a general entity, making no distinction between thermal and hiding cover. Although existing definitions for each are quite clear; in practical application it is frequently difficult to separate the two. From this study, 70% of all bedsites with canopy closure $\geq 50\%$ qualified as hiding cover, and 60% of those with canopy closures $\geq 65\%$ also qualified. Since in the former case we are dealing with 98% of the bedsite population, during the summer months primary selection is obviously for thermal rather than hiding cover. The following is not intended to detract from the importance of hiding cover, particularly since many animals will still be on summer range when the hunting

seasons begin. However, it does suggest that hiding cover alone is of limited value during the summer months as adult elk do not use it for extended periods of time due to the existing thermal conditions. If we accept 50% canopy closure as the minimum threshold for thermal cover, only one bedsite from our entire sample occurred in hiding cover alone. This seems to suggest that on summer range, the full cover compliment should exist in the form of thermal cover that has an adequate hiding cover component within it. The R03WILD model may already be oriented in that direction. Matrix cells which have cover values inserted, all seem to have been selected on the basis of thermal cover (Table 3). Structural stage 2, with its potential for high stem densities and obvious hiding cover capability, was not selected.

Two radio locations per month have been obtained for each study animal. These will enable us to construct summer home range boundaries. Aerial photo interpretation can then be used to determine existing thermal cover/forage area ratios within the seasonal home ranges. This information will be included in the final report. But, it will not tell us what percent of any seasonal home range qualifies as hiding cover.

Bedsite Species Composition. The accepted definition of summer thermal cover restricts all considerations to coniferous species. On our study area two deciduous species (Gambel Oak and New Mexico Locust) occur in noticeable quantities. Gambel Oak in particular contributed heavily to both the canopy closure readings and the stem density and mean diameter values assigned to the bedsites (Table 6).

Table 6. Mean basal area of bedsite plots (sq. ft/acre) within species and diameter classes.

Species	Diameter Class			
	1.0-4.9	5.0-8.9	9.0-12.9	13.0>
<i>Pinus ponderosa</i>	125.7	170.5	187.5	134.4
<i>Abies concolor</i>			22.6	
<i>Cowania mexicana</i>	.4			
<i>Robinia neomexicana</i> *	7.4			
<i>Quercus gambeli</i> *	112.2	64.8	34.1	195.9
TOTAL	245.6	235.3	244.2	330.3
% Deciduous sp.*	49	28	14	59

SUMMARY

Ninety-eight percent of elk mid-day bedsites occurred where canopy closures were $\geq 50\%$. Relative habitat capability ratings for the canopy closure classes

of 50-64%, 65-74% and 75-100% appear to be 1/11, 1/3 and 1/1 (full) acre value; and might be appropriate for use in the R03WILD modeling process.

Seventy percent of our thermal cover sites also qualified as hiding cover. However, selection was primarily for thermal characteristics as 98% of all observations occurred when some level of thermal protection was present. Gambel oak was a significant component of the vegetation at bedsites.

SCHEDULE

The Final Report is due June 30, 1991. Field work in ponderosa will terminate August 31, 1989. Target levels for the summer of 1989 are 30 ponderosa and 30 P/J bedsites. Target level for the summer of 1990 is 30 + bedsites in P/J.

LITERATURE CITED

- Black, H., R. J. Scherzinger and J. W. Thomas. 1976. Relationships of Rocky Mountain elk and Rocky Mountain mule deer habitat to timber management in the Blue Mountains of Oregon and Washington. pp. 11-31. In S.R. Hieb. (ed.), Elk logging-road symposium proceedings University Idaho. 16-17 Dec. 1975. Moscow.
- Brown, R. L. 1987. Effects of Timber Management Practices on Elk, A Problem Analysis Report Arizona Game and Fish Department publication. Project W-78-R, WP4J22.
- Byford, K., L. Fager, G. Goodwin, J. McIvor, and R. Wadleigh. 1984. Wildlife Coefficients. Unpubl. Tech. Rep., US Forest Service, USDA Region III.
- Cotton, E. and J.T. Curtis. 1956. The use of distance measures in physiological sampling. Ecology 37:451-460.
- Leckenby, D. A., J. F. Ely and J. E. Dealy. 1985. Eastern Oregon Cover Study: Direct Observation of Elk and Deer Habitat Use in the Blue Mountain Region of Oregon and Washington. Study Plan. ODF&W 1-4-8-65-70 sub H. PNW II-B-2-6. pp. 24 and 25.
- McTague, J. P., and D. R. Patton. 1989. Stand Density Index and Its Application In Describing Wildlife Habitat. Wildl. Soc. Bull. 17:58-62. pp. 58-62.
- Thomas, J. W., H. Black Jr., R. J. Scherzinger, R. J. Pederson. 1979. J. W. Thomas (ed.). Wildlife habitats in managed forests the Blue Mountains of Oregon and Washington. Agriculture handbook No. 553. USDA Forest Ser.

Scheduling Timber Harvests for Wildlife, Allowing Well-Defined Violations to Age Class Nonadjacency Constraints¹

Thomas E. Gross and Dennis P. Dykstra²

Abstract.--We give an overall view of our results on generalizing the geometric effect of maintaining a minimum difference in age class between any two adjacent timber stands scheduled for harvest on any map, over the length of a rotation. Then we analyze the effect of systematically relaxing this constraint on minimum age difference.

INTRODUCTION

Many national forest plans specify that areas where harvesting is allowed be put into regulation through the establishment of small evenaged timber stands. Each forest is divided into units called management areas, compartments, blocks or some other title which implies an area of approximately 5000 to 20,000 acres. These larger areas are to be entered for the purpose of harvesting timber on a regular interval, often 10 years. A number of the timber stands (which are usually around 60 acres) in each compartment are to be harvested individually during each entry, thereby establishing a cohort of evenaged (regenerated) stands comprising an age class. In most of the plans where "nonadjacency constraints" are defined, stands of the same age class must not be adjacent. In addition, many forest plans state that stands spanning several age classes cannot be adjacent. This process is intended to provide an increasingly diverse habitat for wildlife as the compartment is brought into regulation. We call these rules that restrict the age class difference between neighboring timber stands Temporal Nonadjacency Constraints.

Our preliminary work (Gross 1989, Gross and Dykstra 1989) established that the strict imposition of constraints on the adjacency of timber stands in order to enhance the horizontal and vertical diversity of the vegetative overstory

was impractical. We found this to be so for several reasons. Most important was the extreme difficulty of using mathematical programming to find optimal economic management regimes for an area made up of small evenaged stands while adhering to even the simplest constraints on age-class juxtaposition throughout an entire rotation. In addition, finding even a feasible harvest schedule for an area made up of stands all having the same "worth" in terms of economic return or physical production while maintaining both a non-declining even flow and constraints on adjacency was not practical using mathematical programming. However, our research did show some of the temporal and spatial patterns brought about by several different adjacency constraint formulations when applied to the same map. We also calculated a simple index of spatial and temporal diversity that can be used to compare the patterns produced over time for different rigidly-enforced nonadjacency constraints. The diversity index of a map that had all of its stands scheduled for harvest without violating the adjacency constraint was compared to the index computed for the same map with the same number of age classes where harvest dates were randomly assigned. This paper explores the middle ground between strict application of adjacency constraints and random assignment of harvest dates by showing what happens when well-defined violations of temporal nonadjacency constraints are allowed to occur during a rotation.

METHODS TO RELAX NONADJACENCY CONSTRAINTS

Some forest planners and wildlife biologists realized that strict compliance to stated constraints on adjacency of regeneration cuts might severely restrict options for the placement and timing of those harvests. They could foresee

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²Thomas E. Gross, research associate, and Dennis P. Dykstra, professor, School of Forestry, Northern Arizona University, NAU Box 4098, Flagstaff, AZ. 86011.

in general what we later showed specifically (Gross and Dykstra 1989, Gross 1989). For instance, in our initial research we found that a schedule of final removal cuts strictly following nonadjacency constraints outlined in the Kaibab National Forest plan may require up to 140 years before the stands cut in the first entry could again be harvested. The assumed biological rotation age on the Kaibab is 120 years. The nonadjacency rules lengthen this biological rotation age by 20 years at the outset. Even achieving the regulation of a tract in 140 years comes with several built in suppositions. Most important is that the entire 140-year schedule be planned before initial harvests are begun, and be strictly followed throughout the first rotation. Initial volume targets based on the constraint of non-declining evenflow can only be implemented after it is known whether the geometric and spatial pattern demanded by the nonadjacency constraints allows the anticipated flow over a series of harvests from stands very likely to contain different volumes of timber. Failure to account for the geometry over the entire rotation may cause the violation of non-declining evenflow even if the timber volume to sustain the initial target is present when the violation occurs. This volume may merely be in the wrong place. Furthermore, any deviation from the schedule once it is begun (e.g., one of the stands to be logged in year 40 burns in year 19) is very likely to lengthen the rotation age for the area, and the harvest of some stands will be deferred well into what was to be the second rotation period.

A general realization of the kind of difficulty mentioned above may have prompted planners (Forest Service 1987a and 1987b) and wildlife biologists (Salwasser and Tappeiner 1981) to state adjacency guidelines in less restrictive ways, as in the following extract from the Coconino National Forest plan (Forest Service 1987a):

The following minimum factors are considered in obtaining stand diversity.
The presence of one or more of these factors constitutes a difference between stands.

- Stand age - ± 20 years difference in measurable age.
- Density- $\pm BA 30 ft^2$
- Average Stand Diameter - ± 4 inches.
If average stand diameter is larger than 18 inches, then this parameter will not be used.
- Species composition differences are determined by the ID team, *depending on the project or sale objectives.* Overstory and/or understory species are evaluated.

The sentence between the asterisks is from an amended version of the 1987 plan. Italics are added for emphasis.

From the Kaibab National Forest plan (1987b):

To improve horizontal diversity, *avoid* seed cuts in stands adjacent to a seedling stand, sapling stand, or a stand in regeneration.

We interpret this to mean a ± 30 year age difference between adjacent stands.

From Salwasser and Tappeiner (1981):

Regeneration should be scheduled so that adjacent stands have *at least 80 percent of their common boundary* with at least a two decade age difference.

Discussion of the Coconino Nonadjacency Constraints

The first three Coconino National Forest constraints would give a mathematician who specialized in set theory, combinatorics, and forestry a good deal of work drawing general conclusions about the union of three interrelated non-independent sets. The fourth constraint will cause environmental groups to question the degree of intent on the part of the Coconino to implement any of the previous three, since vegetative species diversity and diversity in the ages (or densities or average diameters) of a collection of stands (of an assumed single species) are two different measurements. If the aim of nonadjacency constraints is to promote a diverse habitat for wildlife by juxtaposing a collection of small land areas so that any neighboring pair differ in the size and density of the overstory, then a measure the resulting wildlife species diversity is more appropriate as an alternative measure rather than plant species diversity.

Yet, there is an explicit temporal nonadjacency constraint (the first), and there are two implied temporal nonadjacency constraints (the second and third). Whatever constraints apply, all the neighbors of an individual stand must comply, even if for different reasons.

The Constraint on Basal Area

Whether or not a newly regenerated stand will reach a basal area of $30 ft^2$ in 20 years is a predictor subject to high variability. A stand containing 1000 trees per acre of 3 in average diameter would have $49 ft^2$ of basal area. A stand containing 600 trees per acre of 3 in average diameter would have about $30 ft^2$ of basal area. A stand containing 120 trees per acre (the minimum acceptable stocking level) of 4 inch average diameter would have about $10.5 ft^2$ of basal area. Such a minimally acceptable stand would not reach $30 ft^2$ until an average stand diameter of 6.8 inches occurring somewhere near year 40 (Pearson 1950), assuming no mortality. Using the value of 400 surviving seedlings (Larson and Minor 1983, Heidman 1988) an average diameter of 3.7 inches

would have to be attained in 20 years to make the second nonadjacency constraint binding.

The Constraint on Average Diameter

A reading of Pearson (1950) leads to the conclusion that southwestern ponderosa pine is unlikely to reach an average stand diameter of four inches in 20 years. On average both the basal area constraint and the average diameter constraint could be expected to be redundant to the constraint on age difference.

All three of the single species attributes (age, density, diameter) can be changed in existing stands, not just upon establishment of a newly stocked stand. If a stand consists of an old growth overstory and a 70 year old understory, it can be changed in "age" from 200+ years old to 70 years old by removing the overstory. Average stand diameter and basal area are always changed when thinning occurs, and some precommercial or commercial thinning could be delayed. However, no "mid-rotation" change in a stand attribute will remove an adjacency conflict due to the establishment of a newly regenerated stand; only the passage of time or a "finding" of differing "species diversity" by the ID team can do that.

We conclude that the Coconino must rigidly apply a 20 yr. minimum age difference in establishing new evenaged stands.

Discussion of the Kaibab Nonadjacency Constrains

Although words like "avoid" are guaranteed to attract the attention of those who doubt that any actual avoidance will occur, the Kaibab's nonadjacency constraint precisely states the only practical way to take stand adjacency into account. What remains is to find an acceptable measure of avoidance.

Discussion of Salwasser and Tappeiner Nonadjacency Constraints

Salwasser and Tappeiner (1981) introduce the way many forest planners try to deal with the uneasy feeling that nonadjacency constraints may be too binding on site specific management. If a well-defined level of constraint violation can occur, then those constraints may not reduce the annual allowed harvest or extend the rotation age. In this way the Kaibab could "avoid" the minimum rotation age of 140 years that results from the strict application of their nonadjacency constraints (Gross 1989).

Several difficulties arise in the interpretation of the Salwasser and Tappeiner (1981) nonadjacency constraints. As quoted, Salwasser and Tappeiner seem to be saying that a single pair of stands must have 80% of that particular stand-to-stand boundary in compliance. This state of affairs is a bit difficult to imagine, since

either one of the pair is harvested in its entirety or it is not, and if not, either there has been no harvest or a third "new" stand has been created that makes up the 20% of the former stand-to-stand boundary that can be in noncompliance (and therefore harvested). This sort of "when is a stand not a stand - argumentum ad infinitum" belongs in the realm of metaphysics, not forest planning. It leads to doughnut-shaped stands suddenly appearing on stand maps or a pattern of clearcuts with narrow buffer areas between them. Our results indicate that neither of these strategies circumvent nonadjacency constraints (Gross and Dykstra 1989, Gross 1989).

If we amend the rule and state that as a minimum, 80% of each stand's entire boundary must comply with the stated 20 year age difference there are still problems. By specifying a percentage of a stand's lineal boundary that must comply, a continuous function is applied to a set of discrete entities, namely the set of stand-to-stand borders a particular stand has. Outcomes for this 80% rule will be different for different stands. For a stand that has few neighbors perhaps none of its shared boundaries can be in violation, and for a stand having many neighbors perhaps three or more of its shared boundaries will be freed from the nonadjacency rule. To allow a percentage of each stand's boundary to be in noncompliance creates a desirable characteristic of flexibility in meeting the dispersion goals for management areas with different spatial arrangements. But, the percentage approach immensely complicates the already immensely complicated task of actually assigning harvest dates to a collection of timber stands.

An Alternative to the 80% Rule

We analyzed constraint relaxation using the same basic approach as Salwasser and Tappeiner (1981). We assume that the idea of having at least 80% of a stand's boundary in compliance with some stated nonadjacency constraint represents a consensus among wildlife biologists. Instead of using some percentage of an individual stand's boundary as the compliance target, we restrict the number of neighboring stands that may fail to meet the minimum age class difference specified in the nonadjacency constraints. Over the entire compartment (management area, or 10k-block), the average compliance using this method can approximate the 80% rule for the following reasons.

Although individual stands may have more or fewer, the map-wide average for the number of neighbors per stand can be no greater than six (Ore 1963).

The average number of neighbors per stand for a typical stand-map will be around five, if the stand boundaries shared with stands in the adjacent compartment are not taken into account.

Therefore, by allowing one nonadjacency constraint violation per stand, the 80% rule will be met on average (i.e. approximately one out of five shared boundaries) within the compartment as a whole. For this analysis we assume the any compartment-to-compartment violations will not be taken into account.

METHODS

Definitions and Assumptions

In order to draw some general conclusions about the effect nonadjacency constraints and the permitted violations of these constraints will have on harvest scheduling, non-declining even flow, economic optimization, and rotation ages of forest areas managed primarily for timber production, we need to define the terms of the analysis and clarify assumptions.

Definitions:

Age Class. A group of individual timber stands each containing trees that are considered to be the same chronological age or within a small well-defined range of age.

Harvest Entry. A planned return to an area for the removal of mature timber. The harvest entry may also be called simply an "entry".

Timber Stands. Tracts of timber land that are harvested with the goal of timber production and regeneration (clearcut, shelterwood cut, seedtree cut) or left standing until some future harvest entry.

Compartment, Management Area, 10-k Block. The area of land over which stand-level planning is done.

Temporal Nonadjacency Constraint. Any rule that stipulates a minimum difference in age between any timber stands that are geographically adjacent. The term "adjacency constraint" is synonymous.

Exclusion Period. The age a recently regenerated stand must attain before any of its immediate neighbors can be harvested. The exclusion period is denoted by E.

Return Period. The time period that elapses between two successive harvest entries into a management area, 10-k block, or compartment; also called "harvest entry period", "entry period", or sometimes the "cutting cycle." The entry period is denoted by R.

Timber Rotation Age. The time that elapses between the establishment of a new timber stand and the maturity of that stand. Maturity can be in biological or economic terms. The term "rotation age" is taken to mean the timber rotation age not the nonadjacency rotation age.

Nonadjacency Rotation Age. The minimum amount of time that must elapse between the establishment of a timber stand (upon the removal of the previous overstory) and its subsequent second harvest, purely as a consequence of the imposition of temporal nonadjacency constraints. This "minimum" amount of time is actually a "maximal minimum"; it is a "worst case" minimum, and specific maps may have nonadjacency rotation ages that are less than this theoretical minimum.

Planning Horizon. The time span over which a solution to a mathematical programming formulation is generated.

Area or Volume Regulation. The goal of harvesting approximately an equal area of land or equal volumes of mature timber during each harvest entry.

Number-of-Stands-Per-Entry Regulation. The type of regulated condition imposed by adjacency constraints. If an equal number of timber stands can be harvested during each harvest entry, all stands in a compartment would have to contain equal volumes of timber or be of equal area to achieve volume or area regulation.

Nondeclining Even Flow. The desire to sustain fairly even yearly timber yields in perpetuity without a decline in volume (Dana and Fairfax 1980).

Assumptions:

- 1) All timber stands are assumed to be in mature condition, and able to be harvested.
- 2) All timber stands in the compartment are candidates for harvest. Any stands that are to be excluded, for any reason, are not represented in the analysis.
- 3) A regulated forest of small evenaged timber stands is the goal.
- 4) Upon regulation, each stand is harvested again when it reaches rotation age.
- 5) The harvest and regeneration of each stand occurs simultaneously.
- 6) The harvest entry period is constant over a rotation, and all stands chosen for harvest

are to be cut at the beginning of each harvest entry. Each time a harvest entry occurs, a cohort of new stands belonging to the same age class is established

- 7) The economic "worth" or volume contained in each stand is equal. That is; all stands are equally desirable as candidates for harvest in any harvest entry.
- 8) The harvest of an approximately even number of stands during each harvest entry is an option, and the analysis can be run with or without this condition.
- 9) The harvest of one or more timber stands is to occur during each harvest entry during a rotation.

These assumptions certainly represent an idealized view of forest management directed toward the sustainable production of timber with the consideration of wildlife via nonadjacency constraints, but without regard to physical production or economic optimality. For some nonadjacency rules, maps of arbitrary size can be drawn that will never meet the ninth assumption (Gross 1989).

Study Goal

This analysis has one simple-to-state goal. Find the minimum number of age classes necessary to allow the assignment of a harvest date to every timber stand represented on any stand map without violating the stated nonadjacency constraint more than one time per stand. In other words, remove all other constraints on the selection of any stand at any time except the relaxed nonadjacency constraints. Given this goal, the assumptions stated above ensure that the problem is formulated in its simplest terms. As a result, a more complicated (typical) problem formulation can be expected to dictate that as many, if not more, age classes be used. The total number of age classes necessary to assign a harvest date to every stand in a compartment without breaking the nonadjacency rules (even the relaxed rule just stated) determines the nonadjacency rotation age.

Coloring Maps

Assigning a harvest date to individual timber stands subject to nonadjacency constraints can be thought as a map coloring problem. Specifically, this type of problem has been given the name "chromatic scheduling" (Wood 1969). Map coloring is a legitimate area of mathematics; contrary to the impression of those who insist on giving us boxes of crayons and coloring books. It is included in the mathematics of graph theory. Graph theory provides the mathematical framework covering most allocation, scheduling and network problems.

Our work is an extension of what is called the four-color theorem. The infamous (at least to mathematicians) four-color theorem remained one of the great unsolved problems in mathematics until Appel and Haken (1977) completed a proof which capped a century of work by many mathematicians. The four-color theorem is simple to state; "To color all the regions of a map drawn on a plane or sphere so that no neighboring regions are given the same color will never demand the use of more than four colors." Proving that there was no counterexample to this claim was very difficult.

Coloring Maps with Strict Adherence to Nonadjacency Constraints

We formulate our map-coloring problem by using the definitions of the return period, " R " and the exclusion period, " E " stated above. Find E/R , and if this quotient is not an integer raise it to the next higher integer value. For instance, the Kaibab constraints are interpreted to require a 30 year exclusion period. If individual compartments on the Kaibab are entered every 30 years for harvesting, then $E/R = 1$, and each time a harvest entry is made a new 30-year age class is established. If a map is prepared using, say, the color red for all stands that will be harvested in the first entry, the color blue for all stands that will be harvested in the second entry, and so on, the four color theorem says that we will never need more than four colors to fill in the stand map so that two red-colored stands are never adjacent, etc. Since each color represents the span of 30 years, the Kaibab nonadjacency constraints will not be violated as long as the map is "properly" colored using the colors that represent the four 30-year age classes. Four 30-year age classes means a nonadjacency rotation age of 120 years, which coincides with the assumed biological rotation age on the Kaibab of 120 years. Note that $4*(E/R)$ gives the number of age classes that may be needed to color the map. Since the "span" of each age class is R , simply multiplying $4*(E/R)$ by the number of decades or years defining R gives the nonadjacency rotation age.

Perhaps the establishment of only four age classes in a mosaic on the landscape is not considered to be "diverse" enough. A fifth or sixth age class (color) could be added, but the nonadjacency rotation ages would become 150 and 180 years; found using $5*(E/R)*R$ and $6*(E/R)*R$. However, there is another way to provide more age classes, and that is by setting the return period to be less than the exclusion period.

Again, we use the Kaibab nonadjacency constraints where E remains 30 years, but now we let $R = 10$ years. The ratio, E/R becomes 3, and we may conjecture that the number of age classes called for will be $4*(E/R)$ or 12, and that the nonadjacency rotation age will remain $4*(E/R)*R$ or 120 years. Unfortunately, it is easy to provide a map that cannot be colored using the 12 age

classes. So the number of colors that will be needed to color any possible map when $E/R = 3$ will be more than 12.

Suppose we pick one of the stands on a stand map and assign it a harvest date of 60 years from the present. As shown above, when the exclusion period was the same as the return period, $E/R = 1$, and $E = 30$, four age classes are needed to "color" the map. Adjacency conflicts can be avoided by simply assigning to the stand's neighbors one of the three other age classes (i.e. years 0, 30, or 90). However, if the exclusion becomes three times the return period, ($E/R = 3$, $R = 10$, and $E = 30$), there will be several age classes that cannot be assigned to the neighbors of the stand that was just assigned a harvest date of year 60. Instead of only year 60, the years 40, 50, 70, and 80 are also prohibited from being assigned to any neighboring stand. We have assumed that it is desirable to have all age classes represented somewhere on the stand map, and the result is that as many as 14 10-year age classes will have to be used to completely color an arbitrary stand map (Gross 1989). This means that the nonadjacency rotation age for the Kaibab, if the constraints are rigidly enforced, is 140 years, as opposed to a biological rotation age of 120 years. In other words a "cost" is paid for the benefit of having 14 10-year age classes juxtaposed on the stand map rather than just four, but this is much less than the cost of providing 14 distinct 30-year age classes.

The Kaibab example serves to show a difficulty in the practical application of the definition of the nonadjacency rotation age. Having a nonadjacency rotation age of 140 years means that any map, no matter how cleverly drawn, can be completely "colored" to meet the rules with no more than 14 10-year age classes. Although we can easily draw a rather convoluted strange-looking map that does, indeed, demand that 14 colors be used, most everyday stand maps can be colored with 13 age classes, and often with 12 age classes. For instance, a checker board stand map can be colored to meet the Kaibab nonadjacency constraints using no more than seven 10-year age classes (Mealey et al. 1982). To go on and assume that all maps can be scheduled with seven age classes (Mealey et al. 1982) is an error.

Suppose, that upon reflection, it is concluded that humans armed with sophisticated measuring equipment might have a difficult time discerning the "edge effect" between two successive age classes out of 14 naturally regenerated age classes, let alone the wildlife, and that fewer age classes would suffice. The Coconino's temporal nonadjacency constraint having an exclusion period of 20 years coupled to a return period of 10 years may provide a suitable number of age classes. In this case $E/R = 2$, and the hypothetical stand on the map scheduled to be harvested in year 60 would only be proscribed from being next to stands harvested in years 50,

60, and 70. Again, if we assume that some stands somewhere on the map should be assigned harvest dates of years 50 and 70, the number of age classes needed to color the map will be nine (Gross 1989). Nine age classes each spanning 10 years will give the Coconino National Forest a nonadjacency rotation age of 90 years. Since the Coconino's assumed biological rotation age is 120 years they may be spared the situation of having to "avoid" violating their nonadjacency constraints. This is fortunate, since their current plan assumes strict adherence to the rules. The Kaibab could also implement adjacency constraints where nine age classes are all that is required to color their stand maps. If their exclusion period remains 30 years and a return period of 15 years is used, then 9 age classes will be needed. This gives a nonadjacency rotation age of 135 years.

The Kaibab has made a nonadjacency rule based on an exclusion period that is one-fourth the biological rotation age. If the nonadjacency constraints are strictly enforced, the Kaibab will not be able to juxtapose more than four age classes, (where $E/R = 1$), of small evenaged timber stands without exceeding the desired biological rotation age of 120 years. On the other hand, the Coconino has an exclusion period that is one-sixth the biological rotation age. As a result, the Coconino can implement four age classes in a rotation age of 80 years, nine age classes in a rotation age of 90 years, or even 14 age classes in a rotation age of 98 years (the next higher integer value of $(20/3)$ times 14). Therefore the Coconino seems to have much more flexibility in the actual implementation of a harvest schedule.

There are two other results of our previous work (Gross 1989, Gross and Dykstra 1989) that diminish any apparent advantage the flexibility of a shorter nonadjacency rotation age would give the Coconino over the Kaibab in setting up an optimal harvest schedule while strictly following nonadjacency constraints. By optimal we mean that the compartment produces the maximum amount of timber possible or the most valuable amount of timber.

- 1) Provided the compartment is to be modeled using mathematical programming (e.g. FORPLAN), the attainment of a regulated forest within the nonadjacency rotation age or the maintenance of nondeclining even flow over a rotation, demands the use of a planning horizon that is at least the length of one full nonadjacency rotation.

Every stand in the entire compartment must have a harvest date assigned before harvests are begun or there will be no guarantee that unscheduled stands will be in the correct locations at the correct time relative to stands already scheduled. Any stands that are not in correct locations at some future date may have to be given harvest dates that are beyond the end of the nonadjacency rotation age. If a schedule of harvests in a compartment on the Coconino is

made using a 40 or 50-year planning horizon instead of the 90-year planning horizon dictated by the nonadjacency rotation age, the logging of some stands that were not assigned to the harvests planned from years zero to 50 might have to be delayed beyond 90 years, and possibly past the 140 year nonadjacency rotation age of the Kaibab. Because of the restrictive effect of nonadjacency constraints on spatial arrangement, once an extended rotation is forced upon them, planners, at some future date, will be unable to shorten future rotations down to the minimum attainable on the Coconino. The effect on yearly volume predictions can be nothing other than negative from the point of view of timber production. No meaningful estimate of sustainable yield can be made unless the spatial arrangement of all the stands available for timber production is taken into account for as long as it takes to have one harvest occur in each of these stands.

Even if a forest planning team was willing to plan a schedule of harvests for a compartment over a full nonadjacency rotation, there would be extreme difficulty in ever changing the schedule once it is put into motion without extending the rotation age. Therefore the planners would not only have to be willing to plan, but they would have to be willing to believe that their schedule would actually come to pass precisely as predicted.

- 2) It is virtually impossible to model an optimal harvest schedule while implementing nonadjacency constraints for more than a few stands by using mathematical programming (Garey and Johnson 1979). If our definition of "optimal" is simply to log every timber stand in a compartment in the shortest period of time without ever violating a nonadjacency constraint, no method known can promise to produce this optimal harvest schedule of discrete entities (timber stands) any more efficiently than a blind search through all possibilities (Lawler 1976, Garey and Johnson 1979). Other definitions of optimal (e.g., maximum physical production or maximum economic return) are as difficult as the simpler problem just stated. Problems of this type are formally known in applied mathematics as NP-complete (Lewis and Papadimitriou 1978, Stockmeyer and Chandra 1979, Hopcroft 1984, Karp 1987, all are excellent articles and not extremely technical).

Although we can state precisely how to do so, and we can show that the process definitely has a solution, no algorithm exists that can guarantee finding an optimal solution to a map coloring problem that is more than about 20 regions in size within a "reasonable" amount of time. We attempted to color a 48-region map to meet the Coconino nonadjacency constraint by using only eight colors. We sought only a "feasible" solution (all regions were of equal "worth"), and formulated the problem as a 0-1

integer program using a branch and bound algorithm. This design meant that the first feasible solution the algorithm "ran into" would be good enough. In this case any "feasible" solution is equivalent to an "optimal" solution. The problem ran for over seven days of central processing unit time on a Digital Equipment VAX 8350 ¹ computer without finding a solution, or even indicating whether there was a solution (Gross and Dykstra 1989). We later successfully colored this map to meet the 8-color conditions outlined in the mathematical programming formulation, but we did so by hand - in about an hour. We found out in practice what others found in theory (Garey and Johnson 1976, Garey and Johnson 1979).

Allowing exceptions to nonadjacency constraints will not alleviate the two problems mentioned above. We continue only as an academic exercise, and with the vain hope that current attempts to reduce constraint sets for FORPLAN formulations of nonadjacency constraints or any other device to find optimal regimes will also be looked upon as merely academic exercises (Meneghin et al. 1988).

To summarize our previous results for the number of age classes necessary to comply fully with three nonadjacency constraint formulations:

- 1) If the exclusion period and return period are the same; $E/R = 1$, no more than four age classes will ever be required to assign a harvest date to all stands on an arbitrary stand map, and the nonadjacency rotation age will be $4 \cdot R$.
- 2) If the exclusion period is twice the return period; $E/R = 2$, no more than nine age classes will ever be needed to assign a harvest date to all stands drawn on an arbitrary stand map, and the nonadjacency rotation age will be $9 \cdot R$.
- 3) If the exclusion period is three times the return period; $E/R = 3$, no more than 14 age classes will ever be needed to assign a harvest date to all stands shown on any arbitrary stand map, and the nonadjacency rotation age will be $14 \cdot R$. Actually, all maps we have analyzed can be colored with 13 colors, but we will use the more conservative estimate.

The number of age classes required can be calculated by the formula:

$$\text{Age Classes} = 5 \cdot (E/R) - 1.$$

Coloring Maps When Nonadjacency Constraints Can Be Violated

Permitted Violations

As previously stated, a compartment-wide 80% compliance with nonadjacency constraints will be met, on average, if only one stand-to-stand boundary violation is allowed per stand per rotation. This rule must be further defined when E/R is greater than one, since there is more than one type of stand-to-stand violation possible when $E/R = 2$ or $E/R = 3$.

The only possible violation when $E/R = 1$ is to harvest adjacent stands during the same harvest entry. When $E/R = 2$ not only is there a noncompliance when an adjacent stand is harvested during the same entry, but also if an adjacent stand was harvested during the previous entry or is scheduled to be cut in the next entry. A "next entry" violation is equivalent to a "previous entry" violation if it is expressed from the point of view of that particular neighboring stand scheduled for the "next" entry. A manager may further specify that the single violation permitted is to occur only during the same harvest entry, or only with a stand cut during the previous harvest entry, or with one neighbor logged during either the same or previous entry. When $E/R = 3$ the situation gets more complicated. Again, whether a violation is "previous" or "subsequent" depends only on the harvest date of the particular stand on which the time measurement is based. The single violation can occur if a neighboring stand was harvested two entries before, or one entry previous, or during the same harvest entry. Further specification may state that the violation be only with a stand harvested two periods previous, or only with a stand harvested one period previous, or only with a stand logged during the same period, or only with a stand harvested during one of the three pair-wise combinations of; two previous, one previous, and same period, or, finally, one violation with any of the three.

Some of the "violation rules" just stated make much less sense than others, and so were ignored in this analysis. For example, it makes little sense to permit the single stand-to-stand violation to be either with a neighbor scheduled for harvest two harvest entries previous or with a neighbor scheduled for the same harvest entry, but not with an adjoining stand scheduled for the previous entry. Likewise, when $E/R = 2$ or 3, to permit noncompliance to occur only with a stand scheduled for the same period will cause more serious degradation of edge-to-edge age class difference than accepting an infringement along the border of a stand cut one or two entries previous. Another nonsensical twist to the problem would be to say that there must be one stand-to-stand violation of the nonadjacency constraints. We obviously want the option to

observe the rules where we can, and only break them when we must.

Below is a more formal listing of violations studied. Each of these possible violations is from the viewpoint of whether or not the timber stand being considered for harvest in the current entry period (the referenced stand) can be cut without violating the adjacency constraints of more than one of its neighbors which has been harvested previously.

When $E/R = 1$

One neighboring stand can be harvested during the same entry period as the referenced stand.

When $E/R = 2$

One neighboring stand can have been harvested only during the entry period previous to the entry period of the referenced stand.

One neighboring stand can have been harvested during the entry period previous or during the same entry as the referenced stand.

When $E/R = 3$

One neighboring stand can have been harvested only during the entry period that was two entries previous to the harvest date of the referenced stand.

One adjacent stand can have been harvested either during the entry that was two entries previous or during the entry period immediately before, but not during the harvest entry of the referenced stand.

One adjacent stand can be harvested during the same harvest entry as the referenced stand or the previous entry or two entries before the referenced stand.

Given these rules, the goal is to find the fewest age classes (or, equivalently, harvest entry periods) that will ever be needed to completely schedule (or color) an arbitrary stand map.

Methods Used

Given the four color theorem, if $E/R = 1$, and one boundary per stand can be in noncompliance, then simple logic will dictate the fewest age classes necessary. For problems where E/R is greater than one, and one stand-to-stand border can break the nonadjacency rules, an empirical approach was used to estimate the shortest nonadjacency rotation. The method is simply to color one or more "hard-to-color" maps manually while using the fewest colors possible.

The number of colors found by the empirical method cannot be taken as a guarantee that some counterexample (a map requiring more colors) will never be found. We offer our estimates only as a "strong conjecture" and base them on our experience in map coloring and our reading of the methods used in proving the four color theorem (Appel and Haken 1977). We have reason to assert that conclusive proofs are possible for problems in map coloring where E/R is greater than one (Gross 1989), and that results will be the same as those presented below. The number of age classes necessary to schedule the future harvest of any compartment under the assumptions stated above must be taken as a "working minimum".

RESULTS

When $E/R = 1$

The only possible violation, when $E/R = 1$, is to cut in adjacent stands at the same time. If the number of violations per stand is limited to one, then only adjacent pairs of stands can be in violation in any entry, since the single infraction allowed for one of the pair is also the only infraction allowed for the other. All stands surrounding the pair in noncompliance must not be harvested in the same entry. This situation is equivalent to erasing the stand boundary between the two noncomplying stands. Many pairs of stands could be chosen in the first entry, and many more could be chosen in subsequent entries. But, since these pairs become, in effect, one larger stand that must adhere to the nonadjacency constraint, the number of age classes, and hence, the nonadjacency rotation age will not be reduced. For the same reason, the nonadjacency rotation age for any value of E/R will not be reduced if the only infraction allowed per pair of stands is a "same-period to same-period" violation.

When $E/R = 2$

As stated above, the single violation of nonadjacency rules can happen with a stand that was harvested in the previous harvest entry, or with a stand harvested either in the same harvest entry or in the preceding entry. In the first case, the number of age classes (colors) will be lowered by two from nine to seven. In the second situation, the number of age classes will also be lowered from nine to seven. So, the Coconino can lower its nonadjacency rotation age from 90 years to 70 years using either constraint relaxation. The reason the number of age classes was not lowered further by the second relaxation is because, like the four color case above, a same-period to same-period violation only "erases" the stand-to-stand boundary of the noncomplying pair.

When $E/R = 3$

Strict compliance with the rules can be broken by cutting a stand next to a stand that was harvested two entries previous, or with a stand harvested either two or one harvest entries before, or with one stand cut in one of three entries; the current, one before, or two previous.

In the first case, the number of age classes needed goes from 14 to 12. For the second, 11 age classes will suffice. As in the examples when E/R is two or one, the number of age classes necessary will remain at 11 for the third combination of possible violations. Like the Coconino, the Kaibab would find that the nonadjacency rotation age has dropped. In the first allowable relaxation, the nonadjacency rotation age becomes 120 years which is the assumed biological rotation age. The nonadjacency rotation age is lowered to 110 years in the second and third situations.

DISCUSSION

If the question is, "Will well-defined relaxations of nonadjacency constraints make them less binding in mathematical programming formulations?" The answer is yes. The number of age classes necessary to cover a map and meet the weaker constraints is fewer. It is tempting to conjecture that the number of age classes as stated mathematically goes from $5*(E/R) - 1$ to $4*(E/R) - 1$. There is even a plus, since we can prohibit same-period to same-period violations and still schedule an area using $4*(E/R) - 1$ age classes.

If a further question is, "Can either strict compliance or relaxed compliance be imposed while finding some optimal harvest schedule?" The answer is no. We can find feasible schedules quickly using sequential or backtracking map coloring algorithms (Welsh and Powell 1967, Nijenhuis and Wilf 1978), but the number of age classes used may be many more than the minimum. We can also generate hundreds of these schedules (colorings) and calculate their present net values or potential production. Further research may show that such a method will have a reasonable expectation of stumbling on a "near-optimal" schedule, especially if there is not much variability in worth or productive capacity within the compartment. Such a "fast" coloring algorithm can be included in a heuristic computer-based harvest scheduler that allows some level of noncompliance with nonadjacency restrictions, and permits evenflow targets to be included.

We believe that a more pertinent question is, "Why bother with juxtapositional constraints in the first place?" On one hand, we know of no naturally occurring landscape mosaic that looks anything like a collection of small evenaged timber stands in a regulated condition whose spatial arrangement adheres to temporal nonadjacency

constraints. Franklin (1988) questions whether the establishment of geometrically arranged monocultures promotes species diversity of either flora or fauna. But on the other hand, nature does not imitate the biological effects of a 1000-acre clear cut, not even with "stand replacement" natural fires. Some middle ground is surely better than either.

We advocate that work be done to establish ecosystem-based diversity measures for horizontal and vertical spatial arrangement of flora and fauna. Qualitative and quantitative estimates of changes in diversity over time can be made using geographic information systems coupled to ecosystem models. Prescriptions for optimal resource use can be approached in an iterative manner and modeled over varying time spans (Müller-Merbach 1975). A "fast coloring" algorithm can be used to generate possible spatial arrangements (if we insist on a stand-by-stand approach). The diversity indices of these prescriptions can be checked against the levels desired for those measures. This approach cannot guarantee maximum present net value or maximum physical production or any other optimal measure, but as more iterations are performed more poor solutions are eliminated.

LITERATURE CITED

- Appel, K. and W. Haken. 1977. Every planar map is four-colorable. Part I and II. *Illinois Journal of Mathematics* 21: 429-567.
- Dana, S. T. and S. K. Fairfax. 1980. *Forest and Range Policy*. 458 p. McGraw-Hill, N.Y., New York.
- Franklin, Jerry F. 1988. Structural and functional diversity in temperate forests. In: Wilson, E. O., ed. *Biodiversity*. National Academy Press. Washington D. C. 166-175.
- Forest Service, USDA. 1987a. Coconino national forest land and resource management plan. USDA Forest Service, Southwestern Region, Albuquerque, NM.
- Forest Service, USDA. 1987b. Kaibab national forest plan. USDA Forest Service, Southwestern Region, Albuquerque, NM.
- Garey, M. R. and D. S. Johnson. 1976. The complexity of near-optimal graph coloring. *Journal of the Association for Computing Machinery* 23(1): 43-49.
- Garey, M. R. and D. S. Johnson. 1979. *Computers And Intractability - A Guide To The Theory Of NP-Completeness*. W. H. Freeman and Co., San Francisco, CA. 340 p.
- Gross, T. E. 1989. Use of graph theory to analyze constraints on the juxtaposition of timber stands. M.S. thesis, Northern Arizona University, Flagstaff. 153 p.
- Gross, T. E., and D. P. Dykstra. 1989. Harvest scheduling with nonadjacency constraints. Pages 310-315 in *Proceedings: Society of American Foresters National Convention*. Held October 16-19, 1988 in Rochester, NY. Society of American Foresters, Bethesda, MD.
- Heidman, L. J. 1988. Regeneration strategies for ponderosa pine. *Symposium Proceedings. Ponderosa Pine - the Species and Its Management*. Eds. D. M. Baumgartner and J. E. Lotan. Washington State University Cooperative Extension.
- Hopcroft, John E. 1984. Turing machines. *Scientific American*. 250(5): 86-98.
- Karp, R. M. 1987. Combinatorics, complexity, and randomness. In: *ACM Turing Award Lectures, the First Twenty Years*. The ACM Press, New York. 483 p.
- Larson, F. R. and C. O. Minor. 1983. AZPIPO: a simulator for growth and yield of ponderosa pine in Arizona. *Arizona Forestry Notes* No. 20. Northern Arizona University. Flagstaff, Arizona.
- Lawler, E. L. 1976. A note of the complexity of the chromatic number problem. *Information Processing Letters* 5: 66-67.
- Lewis, Harry R and C. H. Papadimitriou. 1978. The efficiency of algorithms. *Scientific American*. 238(1): 96-110.
- Muller-Merbach, H. 1975. Modelling techniques and heuristics for combinatorial problems. In: Roy, B., Ed. 1975. *Combinatorial Programming: Methods And Applications*. D. Reidel Publishing Co., Dordrecht-Holland. p 3-27.
- Mealey, S.; J. F. Lipscomb, and K. N. Johnson. 1982. Solving the habitat dispersion problem in forest planning. In: *Transactions of the 47th North American Wildlife and Natural Resources Conference*. Wildlife Management Institute, Washington, DC. p 142-153.
- Meneghin, B. J., M. W. Kirby, and J. G. Jones. 1988. An algorithm for writing adjacency constraints efficiently in linear programming models. Pages 46-53 in B. M. Kent and L. S. Davis, eds. *The 1988 Symposium on Systems Analysis in Forest Resources*. USDA Forest Service, General Technical Report RM-161, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.
- Nijenhuis, Albert and H. S. Wilf. 1978. *Combinatorial Algorithms*. Second edition Academic Press. Orlando, Florida. 302 p.

Ore, O. 1963. Graphs And Their Uses. Random House. New York. 131 p.

Pearson, G. A. 1950. Management of ponderosa pine in the southwest. Agriculture Monograph No. 6, USDA, Forest Service. Washington D.C. 218 p.

Salwasser and Tappeiner. 1981. An ecosystem approach to integrated timber and wildlife habitat management. In: Transactions of the North American Wildlife and Natural Resources Conference. 46:473-487.

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Stockmeyer, Larry J. and A. K. Chandra. 1979. Intrinsically difficult problems. Scientific American. 249(5): 140-160.

Welsh, D. J. A. and Powell M. B. 1967. An upper bound for the chromatic number of a graph and its application to timetabling problems. The Computer Journal 10: 85-86.

Wood, D. C. 1969. A technique for colouring a graph applicable to large scale timetabling problems. The Computer Journal. 12:317-319.

Modeling and Integrating Environmental and Public Concerns in Ponderosa Pine Forest Resource Management: Moderator's Comments

**John Keane
Salt River Project**

The papers in this session relate to the two great changes in public land management over the last 25 years. First, managers must now inform and involve the public, or an array of "publics" in their planning. And second, they must carefully evaluate as many as possible of the environmental consequences of their management actions (or lack of actions). These two changes have revolutionized public land management, and they have made the managers' job a good deal more difficult.

Addressing environmental concerns is not easy. The environmental impact assessment process that comes from NEPA and other legislation is far from perfect. At times the process can be slow, confusing, costly and needlessly bureaucratic. At times the process may not adequately identify the impacts or their magnitudes. Still, the fact that at least some portion of mankind's activities are now routinely screened ahead of time for their environmental impact is a monumentally important step forward.

There is still a great deal of work to do before these impact assessments in ponderosa pine forests can be comprehensive, accurate and reasonably useful. There are many species we do not yet know enough about. Our understanding of ecological, hydrologic and other processes is often far more crude than we would like. Still, the manager today has far more models, simulators, etc. with which to predict some of these impacts than were dreamed of just a few decades ago.

Even if we assume that the land manager and his or her staff can accurately identify all of the impacts of a proposed management scheme, the manager can no longer simply proceed to make his decisions guided only by his actual (or

hoped for) budget. The public must be informed and consulted. This country is a democracy, and that fact cannot be ignored in public land management.

Everyone (almost) seems to agree that public involvement is a "good thing". Public involvement is not at all easy to gather or assess, and the public may be far from easy to satisfy. First, there is not one public with a unified voice. There are many groups with different aims and interests. They may have different levels of understanding of ecological processes. They may demand different and contradictory things. Second, how does a manager get good public input? How can he ensure a fair and representative cross section of public opinion, rather than hearing only from the few highly organized, skillful or most vocal special interest groups. How can he get this input with a minimum outlay of his meager resources? Third, what do you do with public input once you have it? What is the best way to forge compromises between competing demands? And, what if the public (with little training and experience) wants management that the trained and experienced land manager thinks is unwise? The manager in the end must make his decisions, even if they are buffeted about by politics, policies, and budgets. The public may not always be right. However, the public and the manager cannot remain at odds indefinitely. Sooner or later, either the manager will educate the public to come around to his point of view, or our political process will slowly work its will on our government bureaucracies and the manager will be out of a job.

It is easy to see, then, why public involvement and environmental impact assessment are such fertile fields for research efforts. Ponderosa pine land management is no exception.

Multiresource Management and Public Involvement¹

Ace H. Peterson and Ryna P. Peterson²

Abstract.--This paper presents a historical sketch of public-agency conflicts and interactions within the multiresource management decisions and programs of Ponderosa Pine Forests. These conflicts and their resolution are presented from the public perspective of effective methodology to reach such resolution and provide a viable partnership in multiresource management.

INTRODUCTION

The context of this paper explores the concepts wherein forest resource management conflicts with public perception of those managements, public involvement and the interaction needed to resolve those conflicts. The purpose and scope of these resolution processes are based upon the experience of the presenters, and the recognized perspective that these experiences reflect and are similar to those experienced by other interested publics in attempts to interact with land management agencies, agency personnel, and practices.

The presentation from the Public's (layman's) perspective, explains the styles and techniques used to effectively interact within multiresource management. Within this context, the public's involvement is explored dealing with both the frustrations of interacting within the processes and the ultimate achievement of reasonable resolution wherein integration of public input into multiresource management resolves conflicts and reaches issue settlement.

HISTORICAL

The concept of public involvement (other than commodity users) in forest resource management, is in reality that of recent time frame. With minor exception, public participation resided with those entities commercial or legislative in nature. Public or citizen involvement

did indeed have such notable champions as John Muir, Theodore Roosevelt and Aldo Leopold; however, the voice of the citizen was rarely heard in dealings of the forest management agencies on the forest lands nationwide.

Forest wide planning and entity involvement for and within National Forest resources evolved through several distinct phases. In this presentation only the major Acts which govern resource management including timber, will be addressed. Acts, Congressional in nature, some of quite some age, are still relevant in today's environment of interrelationships between the resource manager and the citizen public.

In 1876, Congress took two bold steps, modest by today's standards, which started the process leading to other Acts, which today govern public lands, resources, and management. These steps also started the long process leading to Acts guaranteeing citizen participation. The first, introduced by Representative Greenbury L. Fort (Oregon Law Review, volume 64, 1985) of Illinois, stated intent "for the preservation of forests of the National domain adjacent to the sources of navigable rivers and streams of the United States." The second was an appropriation of two thousand dollars for the Commissioner of Agriculture to employ some man of approved attainments for preparation of a wide ranging report on forestry matters. In 1886, Congress established the Division of Forestry. This was followed in 1891 by the Creative Act, passed to set apart public lands and timber. The Transfer Act of 1907 set aside lands for what became National Forests. It is interesting to note, that this time period became the start of the earliest recorded public involvement with the citizen public attempting to direct Forest policy for other than commercial or speculative reasons.

The next era of major resource Acts was the 1960's with the advent of the 1960 Multiple

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²Ace H. and Ryna Peterson are Directors and Forest liasons of the Arizona Wildlife Federation, Scottsdale, Arizona.

Use Sustained Yield Act. During the middle 60's, the public was able to exert pressure on Congress and the resource agencies for more of a voice into the decision making process with minor success. Such organizations as Sierra Club, Wilderness Society, Izaak Walton League and the National Wildlife Federation with their affiliates became leading forces in laying the major groundwork towards true public involvement and resource management change during this era. Public consciousness was awakening. In 1969 the NEPA (National Environmental Protection Act) was passed and signed into law. NEPA finally spelled out the legal process and guidelines wherein the public could be fully involved within management and policy decision making processes. The agencies drafted regulations and policies directing the rules of engagement, and the public needed another whole decade to gear up, digest, and interpret the rights of public involvement.

Other important Acts were passed bolstering the needs and rights of public involvement. The Resource Protection Act of 1972 (RPA), National Forest Management Act (NFMA) in 1976, Federal Land Management Policy Act (FLPMA), the Endangered Species Act, Clean Water and Clean Air Acts, gave the public the voice and tools to further interact within the multiresource management spectrum. However, NEPA passed in 1969, provided the public the basis to reference and implement the various Acts and regulations of resource management. While the light had appeared at the end of the tunnel, progress towards full and equitable participation has still been a slow process burdened by the inertia of resistance to change within the land management agencies and at times the whims of Congressional interference.

PUBLIC CONCERN, EDUCATION, INTERACTION AND PERCEPTIONS OF MULTIRESOURCE MANAGEMENT

This portion of the narrative gives an overview of the public's efforts to come to grips with the management and decisions affecting public land management and the resources on or in those lands. Without a lengthy step-by-step analysis, a picture can still be attained of public concern and frustration in dealing and interacting within the many laws, regulations and policies of public land management. These efforts were hampered, restricted or circumvented by lack of knowledge of these laws, regulations, and policies on the part of the public, and, in some instances, hampered by ideological conflicts between the public and the land management agency, or Congress.

Even though John Muir had awakened public interest in their natural resources early in the 1900's, the major thrust of public involvement and concern evolved in the 1960's. Perhaps for the first time in history, major portions of a populace had the time, education, interest, and resources to pursue conservation goals and

ideals. Citing Muir, Leopold, Rachel Carson, Thoreau, and others, the citizen public entered the arena for participation in deciding the future of their public lands and resources. The public marched directly into a wall of bureaucratic resistance and bounced off into a maze of legalistic misdirection and confusion.

Until the era of the 60's, the public perception of public resource management was one of implied trust in the management agencies and their policies. Indeed, one agency's motto, "Caring for the Land and Serving People" (United States Forest Service), appeared directed toward securing this implied trust. Simply stated, the public perception was one of viewing those who managed the public resources as wise and benevolent managers, keeping the lands and resources for the good of the public, and the Nation.

In time, the public became informed and educated in resource matters, and more voices raised questions of concern. Individuals and organizations became interested in agency decisions and policies affecting lands, waters, wildlife, and other resources. Public interaction raised serious questions regarding uses of public resources, questioned seemingly biased management decisions, and attempted to correct the problems the public had seen or perceived. The citizen public had realized by various means and methods that current management of the times was indeed biased in direction and lacking in meeting all the needs or the public's interest. A lesson quickly learned was when an agency or its personnel spoke of "our land, our trees, our resources," "our" meant the agency's possession and not the public's. Education and participation within the processes and interaction by whatever level taught the public that commodity interests were indeed prioritized and public interests of wildlife, recreation, and esthetic resources were of lower priority whose values were often skewed or biased (constrained was not the buzz word yet) in the broad picture of resource values.

By the 1980's, the public had grasped a firm handle on the how, where, when, and why of resource planning, legal rights of interaction, and intervention in such planning if necessary. The crux of all multiresource management including timber, and especially forest issues and conflicts, would arise in a document entitled the Land Management Plan (LMP).

NFMA (National Forest Management Act), signed into law on October 22, 1976, directed the Secretary of Agriculture to prepare and promulgate regulations for Forest Service planning modeled on guidelines within the Act. NFMA required all contracts, permits, and other legal instruments allowing use of a National Forest, to conform to that Forest's management plan. Finally, the Act required the Forest Service to "attempt" (*italics added*) to complete the new plans by the end of fiscal year 1985 (Oregon Law Review,

Volume 64, 1985). Now the conflicts became focused as to forest management between the Forest Service and the public entities. The Land Management Plans, more so than possibly any other agency action, focused attention on the complexities and ambiguities of dealing with an agency, and the realm of legalistic, interpretative, and negotiative actions within multiresource planning implementation.

PUBLIC CONFLICTS IN INTERACTING WITHIN MULTIRESOURCE PLANNING

The public, through previous interactions in timber sales, mineral entry, grazing allocations, and wilderness plans, had to some extent forced the Forest Service and other agencies out of their protective boxes. The agency's reaction, on the other hand, was similar to an analogy of removing Jello from a container with a pin; lots of movement and some progress, but with a lot of frustration. Much depended upon regional or local forest service personnel as to the amount of progress made. However, on the whole, the agency resisted concrete gains by the public within what the agency interpreted as "their" eminent domain.

The public's attempts to interact within the scope of multiresource management and planning was stonewalled by agency interpretation and methodology. Interpretation of words, phrases, definitions, and procedures varied extremely as to who was interpreting these, agency or public, and in many instances varied from forest to forest. Even the very Congressional Acts, NEPA, FLPMA, NFMA, were interpreted differently as to intent and meaning by both agency, public, and, at times, the Courts.

Methods used by the agency involving, or not involving the publics also created confusion and conflict. The use of minimum notice was intended to satisfy the NEPA requirements of public participation. Notification of hearings, or planning appeared in miniscule wording within the legal section of newspapers next to corporate documents, tax records, repossessions, and the like, or were published in journals located in municipalities far removed from the interested populace. Of course the fine line was these items of notification were published in the National Register, which is not one of the most common household subscriptions. Mailing addresses while purported to be computer updated and complete seldom notified all the interested public participants. In fact, this type of misdirection resembled nothing so much as a portion of a novel, wherein the hero, Arthur by name, awakes to find a highway bypass proceeding toward his house. When Arthur inquired or could we say intervened, he was told that proper notification had been given as required by law. Quoting in paraphrase what

transpired was this: "the legal notice had been posted in the basement of the appropriate department, and because the lights did not work, a flashlight was needed along with a ladder for the missing stairs; in the bottom drawer of a filing cabinet in a disused lavatory with a sign on the door reading "beware of leopard" (The Hitchhikers Guide to the Galaxy, Douglas Adams, 1980). An appropriate example of minimum notice.

Legal definitions and notification of appropriate time frames for response to or intervening in agency decisions became another example of bureaucratic misdirection. Deadlines were hidden in phrases pertaining to Forest Service regulations and never printed in their entirety, pursuant to CFR something or other with all the legal numbers and subsections. The publics often found themselves outside the process because of missing or misinterpreting a response deadline.

The methodology of determining resource values created increasing conflicts with the publics, especially those interested in wildlife, recreation, and esthetic values. Conflicts arose over allocation of resource dollars and management direction pertaining to recreational visitor days (RVD), wildlife-fish user days (WUFD). Just what determined a WUFD? Why were not all WUFDs equal? How long was an RVD? Should WUFDs and RVDs be different in value? Where was the parity between these entities within forests, forest to forest, region to region, or states? Foreplan, the computer model used to generate land management plan data, allocations and values, along with other input, became questioned as to validity accounting for more issue conflicts.

Many more conflicts are both conceived and perceived by the agency's inability to articulate to the public the reasons for, and the processes of multiresource planning and implementation. The public moved by a need or a concern, requires information which can be understood and followed within the process, providing viable input to those plans and or projects of interest.

CONFLICT RESOLUTION IN MULTIRESOURCE MANAGEMENT

The conflicts affecting multiresource management, whether real or perceived by agency or public still exist to a greater or lesser degree. While progress has been made, considerable distance has yet to be covered in totally resolving these conflicts. The public entities feel a need to be involved in the management of public lands and resources. The Forest Service and other agencies are viewed by the public as their resource managers, while the public fulfills the role of stockholder within the management spectrum.

In order to adequately and equitably manage not only timber, in this case Ponderosa Pine, but all resources in a multiresource mode, both

the public and the managing agency must reach agreement through communication and cooperation. Both the publics and the agencies speak of a working partnership, one of equitable relationships toward implementing multiresource decisions. This is only possible when both entities understand the other, and cooperate within the framework of such understanding and cooperation. The era of simple implied trust is past history. However, a mutual trust within the scope of partnership goals and objectives can, and must become reality.

Within this scope of cooperative partnership reside two avenues, along with associated responsibility, which if used, will serve to implement the goals and objectives of true multi-resource management. One of these avenues directs the managing agencies, the other directs the interested publics. One theme must exist, in that these are parallel avenues rather than divergent paths.

Agency/Public Interaction

The guidelines discussed and listed in this portion of the text are intended to provide a system wherein the public can interact with the agencies, and relate to the data required to provide viable input. As discussed earlier, there is a shared responsibility in dealing with multiresource management.

A. Before an agency, such as the Forest Service, can distribute information and program intent, there must be a direction from the public which accomplishes two main purposes. The first is a declared intent by a citizen or organization to become involved. This should take the form of a letter to the office of the agency involved at whatever levels are deemed necessary. Preferably send this letter to the Supervisor's office of the forest or districts to be interacted with. Secondly, the agency must know where to contact the person who expresses this interest. If more than one person is to be involved, specify along with the above information this person's area of responsibility or interest.

The agency, upon receipt of this notification, must place this information in the appropriate files or programs for mailing use along with needed updates. This data must also be disseminated, using the Forest Service as an example, to the districts and to the Regional office.

B. Even though the participant should be receiving adequate notice from the agency on plans, decisions, or projects, it is the participant's responsibility to make themselves aware of such actions via newspaper, newsletter or other personal communication.

The agency has a similar responsibility. Beware of fulfilling only the minimum requirements of the law. This is what those data files of interested publics are for, proper notification via radio, television news, up front in the proper newspapers, and by letter to those persons whose names are in the computer or other files. Too much notification is much better than little or none at all. It is a lot easier to notify than have a project stopped via appeal intervention.

C. The participant needs to keep themselves aware of dates, times and deadlines. The agency needs to make sure these are clear, concise and understandable.

D. Know the agency personnel and citizen representatives that are to be worked with on any program or project. It is far easier to establish a viable working relationship with someone who is known visually as well as by title or signature. Get further acquainted via meetings with each other, rather than just at public hearings.

E. Respect the opposition, if indeed this is how the one views the other. The golden rule, treat as you would be treated, applies here. The agency personnel are not just titles or signatures, they are people with the same human traits as the citizen public. These persons have spent years of their lives learning the resource they manage, plus the education process of college or university.

On the other hand, the agencies need to realize the citizen public have become very well educated in resource matters and the legal processes regarding interaction. Too many times agency personnel tend to fall back on "professional" attitude without listening to or accepting as "value" the public input. The public in many regards are just as professional as the person wearing the agency uniform. Remember, both are after the same end product, and a fresh outside perspective can yield very productive results.

F. Know the regulations and pertinent laws of public involvement. This applies to both parties. It is amazing how many agency personnel are ignorant, at times, in this area. The agency, as their job, should be very knowledgeable in this item. The participant should have available a copy of the CFR code, NEPA, and FLPMA references as a minimum. The agency should take the lead in resolving conflict by supplying these to the interested public when they receive notification of such interest. Appropriate sections of the agency handbook dealing with regulations and techniques of resource management are recommended.

The laws and regulations need to be used by both parties in the intent for which these

were created. Which is to provide clear direction for participation and management. Unfortunately, both parties tend to use these punatively, which in many instances starts conflict where none may have existed.

G. To enable both the agency and the citizen public to communicate, there must either be a common language or an understanding of the language the agency uses in preparing plans or documents. Far too often, either by intent or forgetfulness, what is spoken or written by the agency comes out in acronym form. RVD, AVM, MMBF, WUFD, ROD, CFR, basal area, DBH, shelterwood method, intermediate cut, these and more are commonly used, and the public has no idea what is being discussed. Just as the public needs to learn all the jargon to communicate, the agency would be better advised to speak "layman" and to prepare documents in plain English so both are discussing the same thing. Glossaries of terms should be made available in places and times other than the back of an LMP or EIS.

H. It is not always clear to the public just what the need for a particular project may be, or why the project is designed in a particular manner. The "how, why, what, and where" need to be fully understood by the public, at the earliest point of time in the process.

I. One of the major points of conflict which arise via the project scheduling or implementation, is the "why" factor. Projects are being drafted by the agencies with, at times, no definite purpose in mind, other than the public's perception of cutting trees. Each project should be spelled out up front. The need for, and what the project is to accomplish should be understood clearly by the public and agency alike.

J. The publics need to work within the system without using the ultimate tools of intervention, which are appeals to work within that same system. If the partnership idea is to be feasible, each must strive to accomplish

the plan or project for the mutual benefit of the resource or resources involved. If as a last resort, mutual agreement cannot be reached, the agency must not take "personally" the public's use of appeal or even litigation. The public must also be realistic in the agency's prerogative to forward items of impasse onto their appropriate place of decision.

In conclusion, the points of solution while apparently simple, are just now being defined and addressed within the land management agencies. The Forest Service has implemented programs to instruct their personnel in how and when to involve the citizen public. Other agencies either are, or should be initiating similar programs. We, the public and the agency, are irretrievably linked in managing the resources of our public lands. Each needs to more fully understand the role of the other in this spectrum. Multiresource management must consider the human factor as an integral part of this form of resource management; not in the social or user context alone, but rather as a dynamic team interacting together to benefit all resources including mankind for this and succeeding generations. Perhaps Aldo Leopold said it best when he expressed this philosophy, "we shall never achieve harmony with the land, but the important thing is to strive to achieve" (Sand County Almanac 1949). This quote also speaks true for conflict resolution within multiresource management.

LITERATURE CITED

- Adams, Douglas. 1979. The Hitchhikers Guide to the Galaxy.
- Leopold, Aldo. 1949. The Sand County Almanac.
- United States Forest Service. (date unknown). Agency Motto.
- University of Oregon. 1985. Oregon Law Review, Volume 64.

Multiresource Forest Management with EZ-IMPACT Simulation Models¹

R. W. Behan²

ABSTRACT

The central features of multiresource forest management are a system view of the forest, and the foreknowledge of systemic responses to proposed management activities.

A forest system simulation model is therefore indispensable in the practice of multiresource management. The importance of simulation models, however, is underestimated and underemphasized, particularly in professional forestry curricula, which at least appear to be obsessed with quantified optimization models instead.

The construction and use of simulation models should be important parts of undergraduate education in multiresource management, and are essential in field practice.

A proprietary software product, EZ-IMPACTtm, offers an economical means of constructing judgement-based, situation-specific computer simulation models of forest systems and the social environment in which they are managed.

INTRODUCTION

EZ-IMPACTtm is a proprietary computer program developed and marketed by Biosocial Decision Systems in College Station, Texas (Biosocial Decision Systems, 1987). It provides an economical means of constructing a judgement-based, situation-specific computer simulation model of a forest system and the social context of constituent groups in which it is managed. Various prospective management alternatives can be simulated, to project the impacts on the entire forest system; and the alternatives can be tested against the value-agendas of the

constituent groups, as well. On-site, constituency-based multiresource management is made possible, with an off-the-shelf package of software.

In the professional, scientific literature we don't often, shouldn't often, find endorsements for proprietary products. For the practice of on-the-ground multiresource forest management, however, the EZ-IMPACTtm software is unique and indispensable; until a competing and superior product is marketed, the implied endorsement can't be avoided. (Hereafter I will abbreviate the software package "EZI.")

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²R. W. Behan is Professor in the School of Forestry, Northern Arizona University, Flagstaff, AZ.

EZI isn't purported to be better than everything else: at the moment, as far as I know, there simply isn't anything else. Meanwhile, the product offers multiresource forest managers a capability they can scarcely do without.

SIMULATION MODELS AND MULTIRESOURCE FOREST MANAGEMENT

The central feature of multiresource forest management, which sets it apart from the traditional single-resource, sustained yield paradigm of professional forestry, is a system view of the forest, and a foreknowledge of the systemic responses of the forest to proposed management perturbations.

What is the response of wildlife habitat, for example, or of scenic amenities to the expansion of a road network, or to alternative timber harvesting quantities or techniques? Or what happens to timber growth and harvest in response to various alternative regimes of big game management, or various potential configurations of fire management or wilderness designations?

Only a simulation model can provide prior insights into such systemic responses. And only a computer simulation model can hold hundreds of system components in memory simultaneously, to trace thousands of interactions in any sensible period of time.

As the concept and techniques of multiresource forest management continue to be developed, however, I believe the importance of simulation models is being severely underestimated and underemphasized.

Instead, we are fascinated by, and we are producing a voluminous literature about the role of optimizing models--linear programming applications in particular--in multiresource management. I believe the fascination has become obsessive.

Certainly we are teaching the use of LP models with vigor and verve: textbooks and curricula abound with Z-functions, constraints, coefficients, and the Right Hand Side. Students whale away for hours in the computer lab, running endless iterations, looking for the feasibility polygon's optimal but elusive corner point, in all that hyper-space.

I believe this obsession with optimality is leading our students, and the profession of forestry, in the wrong direction. In a subtle and beguiling way, with little notice and wholly without critical scrutiny, it is creating a professional context or

environment of technical determinism, even technical perfectionism. It is perpetuating the notion that professional land management is preeminently a technical or scientific undertaking. It discounts and discourages the appreciation for, the confidence in, and the development and exercise of sound managerial judgement.

The difficulty here lies not in the shortcomings of the LP algorithm. Nothing in my experience can top it for ingenuity, possibly excepting the G.I. can opener, the Derry-slotted steerable parachute, and thermal-gradient energy generation. I applaud Professor Dantzig for working it out, and his students and successors for developing and disseminating the elegant variations.

The problem lies in our extension of LP solutions into problem levels, magnitudes, or strata where they are wholly inappropriate.

LP optimization models work very well when objectives can be realistically and legitimately quantified, and when the problem is fundamentally simple--adjusting an oil refinery's output of several products, for example--but the possible choices are infinite or nearly so. These might be termed "tactical" problems.

Tactical problems arise in forestry, beyond doubt. When they do, LP solutions might well be in order. But often in forestry, particularly in multiresource forestry, we are dealing with higher-level problems--we could call them "strategic" problems--in which the objectives transcend quantification.

If objectives cannot be realistically and legitimately quantified, LP optimization techniques are useless. This point is rarely overlooked in the teaching of optimization, to the credit of the authors and the adopters of the current textbooks. I believe, however, we overlook it or discount it extremely heavily in a far more profound way: when we decide to emphasize optimization so obsessively in undergraduate curricula in the first place, and continue uncritically to do so.

In my judgement, strategic problems are far more common than we realize, particularly if we define them simply as those that transcend quantification.

Multiresource forest management itself, it seems to me, is fundamentally

a strategic problem. We all agree that most multiresource values cannot be realistically or legitimately quantified, but we fail to act out our convictions. First we use, decently enough, market data to quantify timber and forage values. Then we make some heroic and ingenious efforts to quantify some more, and finally we simply assign or impute values to the rest, for the construction of a hypothetical objective function: thus is made possible the teaching of LP principles.

This is an exercise almost literally in fantasy: but even if all the output values could be legitimately quantified, real-life multiresource management objectives would still not be completely defined.

Management objectives, multiresource or otherwise, characteristically are complex, multiple, often amorphous in the extreme. In the private sector, such things as market share, labor retention, public good will, the long term continuity of the enterprise, and so on and on, are all critically important elements in strategic objectives.

Not at all infrequently do some elements of a multiple, complex, amorphous objective--that is to say a real one--conflict directly with others. Consider the conflict between "customer satisfaction" and "net revenue" for example. Both are essential to the welfare of a firm, and, arguably, they are direct, zero-sum trades.

In the public sector, the difficulties multiply. Objectives here also contain complex, multiple, amorphous elements, but there is a further barrier to quantification not often encountered in the private sector. Because there is a plurality of "owners" of public forests, there is almost always a plurality of prospective "objectives," and almost never consensus. If objectives cannot be agreed upon, they certainly cannot be quantified.

Optimization models, in management situations as complex as multiresource forestry, are intriguing curiosities and devilishly clever, but they depend utterly upon the impossible. In the whole arena of management responsibilities, nothing is more difficult than the specification of strategic objectives; there is good reason to believe it can't be done.

Aaron Wildavsky, Charles Lindblom, and Herbert Simon have been making this argument for years, and I believe their arguments apply to multiresource forest management. In Wildavsky's words, we don't know what we want until we know what we can get; in Lindblom's, the best we can do is to muddle through; in Simon's, we have to settle for "satisficing," not maximizing.

All this is such common knowledge among students of management science there's no need to elaborate it, nor to cite the references. And we can arrive empirically where Wildavsky, Lindblom, and Simon take us theoretically: how often have private forest owners told their forest managers simply and exclusively to maximize PNV? Have American people ever said that to the managers of public forests?

No, real objectives in multiresource forest management cannot well be specified, much less quantified, but we carefully and successfully deny the irrefutable. We continue to instill (and demand) competence, among forestry students, in the use of optimization models--demonstrably useless tools, except at the tactical level, for the practice of multiresource management.

Witness the most conspicuous attempt to use optimization techniques where they are hopelessly inappropriate--the sorry episode of national forest planning. After spending 13 years and 16% of its total management budget for the entire national forest system, and using an LP model seeking to maximize PNV, the U.S. Forest Service has satisfied essentially no one. As I suggested above, there is disagreement over the objectives for which the national forests are managed, but no one, to my knowledge, has been hawking the maximization of present net value. (There may be, indeed, a consensus of opposition, and certainly one of indifference.)

Professor K. Norman Johnson, the architect of FORPLAN, is as sound a critic as anyone I know who has addressed this matter in print. The National Forest Management Act was much more strongly focussed, Johnson argues, on "...the assurance of protection of the forest environment during all actions" than on economic efficiency. (Johnson, 1987.) Sound multiresource forest management, if I may paraphrase Johnson, was more important than maximizing PNV.

The Forest Service selected Johnson's own creation, FORPLAN, as its optimizing model. Nevertheless, he went on to say this:

Selection of an optimization model for forest planning has limited the ability to consider environmental effects in detail in forest planning modeling. I do not believe that an optimization model such as FORPLAN is required by the NFMA. An equally strong argument can be made for models that emphasized the simulation of environmental effects from road building and timber harvesting...

The obsession with optimization is widespread, apparently, and simulation models are underemphasized, insufficiently exploited.

There is one final reason I find the emphasis on optimization unfortunate in the development and in the teaching of multiresource forest management. Optimizing models can only tell us, as we test the production of various alternate output mixes, what happens accordingly to the "objective function": how well we are maximizing PNV, or minimizing costs, or some other strictly determined, quantified objective. Optimizing models do not and cannot tell us what happens in the forest system as the product mix is varied. That is the critical element in multiresource forest management, and only simulation models can do it.

BUILDING SIMULATION MODELS WITH EZ-IMPACT™

Some General Comments

Far more than we do, I believe, we should be teaching the construction and use of simulation models, and touch on optimization as an interesting exercise in the pursuit of idealized perfection, an exercise of occasional but slight applied utility, and one that is avoidable--largely, justifiably, and inevitably.

There are at least two elements inherent in building computer simulators of forest systems that bear on their reliability and the fidelity with which they reflect reality: the character of the data inputs, and the nature of the algorithm, or algorithms, that manipulate the data.

The most sophisticated simulation models use research-generated data and uniquely constructed algorithms

appropriate for that body of knowledge. An example is ECOSIM, a model of high reliability and fidelity developed in the ponderosa pine forests of the Southwest. The problem with this class of models is high cost: ECOSIM took about 15 years and \$5 million to produce.

At the other extreme are models that can use judgement-generated data (even "guesses") about the nature of the system to be modelled, and apply generic algorithms. EZI models fall in this category, and the huge advantage here is low cost: given familiarity with the software, an EZI model can be built in a few hours. I would estimate a very useful model could be produced, iteratively, and by thoughtful, knowledgeable resource managers, in a week.

This is not the place to engage in a pointless debate about the superiority of one class of models over another. Clearly, reliability and fidelity on one hand, and cost on the other, are tradeoffs. For most prospective multiresource managers, I presume, cost and time are stringent constraints: there may be no realistic option to a judgement-based, generic-algorithm simulation model. In these circumstances, obviously, EZI models become irresistibly attractive.

Building an EZI model of a forest system is enormously valuable even if the manager never uses it for testing prospective management activities. It is an intellectually demanding job, and having done a few, I can verify there is no better way of coming to understand the workings of the forest system at hand.

First, the manager is forced to indentify the critical variables in the forest system, and then to describe the relationship of each variable to all the others. Thinking all this through imparts a knowledge of the forest system, and an understanding of its behavior that can be gained in no other way. That is why I think we should be spending far more time in undergraduate forestry curricula building and running forest simulation models.

Details: the Construction and Use of EZ-IMPACT™ Models

The first step in using the EZI software is to name the model. This also designates a data-file that will be stored by the computer. In the example to follow, we will track the ENCHF0R3 model--the third version of a model I

have built for the manifestly hypothetical "Enchanted Forest."

When EZI simulates a management alternative, it does so with a fixed run of 20 iterations. The next task is to distribute those twenty iterations over an appropriate period of time--for how long do you want to observe the system's behavior? First you choose a unit of time--a year, a month, an hour, a minute. Then you choose the time period--a number of units between 5 and 60. Having chosen, say, "minute" and "60", you have designed a model with a "life span" of 60 minutes, and the iterations will take place at 3 minute intervals. In a ten-year model, on the other hand, the iterations will take place every six months. Not much tree growth, certainly, takes place in three minutes, so these choices are not trivial. (ENCHFOR3's time interval is 5 years.)

Next you specify the month and year in which you want the simulations to begin. (ENCHFOR3 fired up in January of 1989.)

The next step may be the most critical. The important variables for your model must be identified and described, and a unit of measure for each must be selected. The software does not use these directly, but forcing model builders to specify measurement units also forces them to sharpen their thinking about the variables. Suppose, for example, "wilderness" is an important variable. What about wilderness is important? Is it the total area, the new area dedicated each year, or the use that is accommodated annually? Appropriate measurement units would be acres, acres/year, and visitor-days/year, respectively.

Next, for each variable, the "maximum feasible increase," the "expected change," and the "external impacts" all are specified, which does a number of important things.

By expressing a maximum feasible increase for each variable, measuring the subsequent behavior of each can be "normalized," and expressed in every case in terms of "percent of maximum." Expressing the maximum also imputes an initial value: if a variable can double over the time-span of the model, its initial value must be 50% of its maximum.

The "expected change" for each variable constitutes the existing management regime; every system has to start somewhere, so EZI is always dealing at the margin.

The "external impact," expressed as a percentage of the expected change, accounts for variables acting from "outside" the model. A certain percentage of acreage burned, for example, will be caused spontaneously by lightning ignition, while the rest is accounted for in controlled ignition; if the model represents the manager's control-arena, spontaneous ignition is an "external impact."

Figure 1 displays the variables in ENCHFOR3. Only variables 1-8 will be active in the simulations to follow, in order to keep this example model simple--64 cells instead of 400. Variables 9-20 are entered with no values, simply to display some other variables that might be included in a working model. (EZ-IMPACT will handle up to 39 variables.)

Note that virtually any kind of variable, even "fuzzy" variables, are accommodated in EZI. I believe this is one of its major virtues: we can be as comprehensive and as realistic as we choose. The only limit is the imagination of the modeller, and the legitimacy of the variable.

Foresters have long struggled with scenic beauty, for example. We have some research-based "scenic beauty estimators" used in ECOSIM and elsewhere (Brown and Daniels, 1984). I have wondered for a long time if we could measure scenic beauty indirectly in the negative, in terms of complaints about its destruction. One of the dummy variables in the model, number 16, is NEGBEAUT, accordingly, and I will appreciate restraint with respect to the obvious play on words.

The selection of variables is deceptively easy, and it is deceptively easy, I found, to choose atrocious ones. DPDRKWDS--Deep Dark Woods--my first attempt at EZI modelling, displayed dozens of them. Done without the advantage of a rough decision rule on selecting variables, Deep Dark Woods turned out to be a useless monster.

My rough decision rule, fashioned much later, is this: include in the model the investment actions and

Figure 1. Variables and trends for ENCHF0R3 Multiresource Model.

EZ-IMPACT
Multiresource Management Model III for the Enchanted Forest

No.	Variable Name	Variable Description	Unit of Measure	Maximum Increase (%)	Expected Change (%)	External Impact (% Exp.)
1	TBRGRWTH	timber growth	mbf/year	100.0	50.0	0.0
2	THN'VEST	thinning investment	\$M/year	200.0	75.0	50.0
3	TBRHRVST	timber harvest	mbf/year	200.0	100.0	60.0
4	DR&ELKPD	deer & elk production	animals/year	100.0	25.0	0.0
5	D&EHRVST	deer, elk harvested	animals/year	100.0	50.0	75.0
6	WLDFIRES	acreage of wildfires	acres/year	1000.0	100.0	75.0
7	WLDRNSS	designated wilderness	thousands acres	100.0	50.0	50.0
8	ROADCON	road construction	miles/year	1000.0	25.0	50.0
9	FORPROD	forage production	tons/acre/year	0.0	0.0	0.0
10	GRAZING	forage consumption	AUM's per year	0.0	0.0	0.0
11	H2OYIELD	water yield	acre ft./year	0.0	0.0	0.0
12	PRESBURN	acreage, prscrb. burns	acres/year	0.0	0.0	0.0
13	DEVREC	developed recreation	visitor days/yr.	0.0	0.0	0.0
14	DISPREC	dispersed recreation	visitor days/yr.	0.0	0.0	0.0
15	NEGBEAUT	ngtve scenic beauty	complaints/yr.	0.0	0.0	0.0
16	INVSTREC	invst.rec.developmts	\$/year	0.0	0.0	0.0
17	REVCOUNT	revenue to counties	\$/year	0.0	0.0	0.0
18	RNGINVST	investmt, range mgt.	\$/year	0.0	0.0	0.0
19	CLEARCUT	acres clrcut per yr.	acres/year	0.0	0.0	0.0
20	PARTCUT	ac.partial cut/yr.	acres/year	0.0	0.0	0.0

Time period is 5 years, beginning 1/ 1989.

activities available to the manager--thinning, road building, fire suppression, harvesting, and other things managers can do to the system--and the biophysical and social variables that will be impacted, accordingly--growth rates, visitation rates, acreage burned, sediment loading, etc. What you want the model to accomplish, it should be apparent (but it wasn't to me initially), should dictate the relevant variables. If you want to project the impacts on the system of prospective management decisions, include the system variables and the decision variables, and leave everything else out. (A parsimonious list of variables is very much to be desired, as we shall see.) I'm ashamed to suggest how long it took me to learn this.

In the next step, managers will come to see their forest as they've never seen it before. They will indeed see the forest, sense the forest, as a system, because the relationship of each variable to all the others must be specified, with four parameters. The "type" of impact can be either long-term and cumulative, or short-term and proportional. (There are some unambiguous definitions of these terms to be applied.) The impact's direction must be specified: is the impacted variable driven up or down? What is the strength of the impact--strong, moderate, or

weak? (Finer distinctions are possible, but might be specious.) Finally, a constraint on the impact can be inserted, if it occurs only when the impacting variable is rising or falling.

This is the step in which you are literally building the model. If there is hard information at hand to guide your specification of the relationships, by all means use it. (A thorough literature review prior to constructing the model, while not necessary, would raise the fidelity of the model, of course--and its cost.) If not, you must rely on judgement--your's and others', which can be augmented effectively if a Delphi process is used. The ways in which data input can be improved are many, each carrying a different price tag.

Foresters who know their forest system and its behavior as well as they should, or as well as they think, can breeze through this exercise. Very few will, in fact, breeze--a measure of our ignorance of how forests really work.

Figure 2 shows the "original model" of ENCHF0R3; it includes all the parameters except the "strength of relationship." (The omission will be explained shortly.)

It is now time to joust directly

Figure 2. Type of impact, direction, and constraint parameters in the ENCHFOR3 model.

EZ-IMPACT

PROJECT: ENCHFOR3
Original Model Multiresource Management Model III for the Enchanted Forest

No. Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1 TBRGRWTH	.	+L	-S C	-S C	-S C	-L	.	.	.	.	.	.	.	.	.
2 THN'VEST	.	.	+S C	.	.	-S C	.	.	.	.	.	.	.	.	.
3 TBRHRVST	+S C	.	.	.	.	-S Up	-S C	.	.	.	.	.	.	.	.
4 DR&ELKPD	-L	+S C	+S C	.	-S C	+S C	.	.	.	.	.	.	.	.	.
5 D&EHRVST	-L	+S C	+S C	+S C	.	.	.	+L	.	.	.	.	.	.	.
6 WLDFIRES	+L	-S C	+S C	.	+S C	.	+S C	-L	.	.	.	.	.	.	.
7 WLDNRSS	.	.	-S C	.	.	+S C	.	-S C	.	.	.	.	.	.	.
8 ROADCON	.	.	+L	.	.	+S C	.	.	.	.	.	.	.	.	.
9 FORPROD
10 GRAZING
11 H2OYIELD
12 PRESBURN
13 DEVREC
14 DISPREC
15 NEGBEAUT
16 INVSTREC
17 REVCOUNT
18 RNGINVST
19 CLEARCUT
20 PARTCUT

with your computer, which expects you to be rational, consistent, and bright. If you have built a good model, and if you have included no logical contradictions, physically impossible feedback loops, or other dumb features, the model should gallop through the specified time period and produce the "expected changes," shouldn't it? Your model should be able to display your current management regime producing the expected results.

It probably won't. We have built the model piece by piece, relationship by relationship, and we simply can't keep all the pieces in our minds simultaneously. The computer can, of course, and does: that is the colossal advantage of computer models, and we should not be offended when the computer asserts this peculiar superiority. But it certainly will, and we will certainly be offended.

This will happen in EZI's "Refinement" process. The user's manual steers us through the debugging process, and when the model can hit the "expected change" values within plus-or-minus 4%, it is declared, by both the computer and the triumphant modeller (with damp palms and a relieved grin), to be "refined."

(The software adjusts the "strength" parameter to accomplish this, which is one reason why an initial three-way discrimination is probably sufficient.)

Figure 3 shows the 8 active variables "refined" to fall within the plus-or-minus 4% standard. (This is a screen-print generated with the MSDOS GRAPHICS command.) Figure 4 shows the "unrefined model," and displays the initial "strength of impact" parameters. Figure 5 displays the "refined model," in which the "strength" parameters have been adjusted. (These are printed out directly by EZI.)

We can check the refined model by running a simulation of the existing management regime, an "experiment" called "EXPECTED." The results are available on screen as a bar chart (Figure 6) or a line-graph (not illustrated), or printed in tabular form (Figure 7). For each variable, the "difference from expected values" is zero, as we would expect.

Now we have a workable model in which, by virtue of its ability to "predict" the expected values we initially specified, we have a fair

Figure 3. "Successful Refinement" screen, showing simulations falling within 4% of expected values.

```

** REFINEMENT IN PROGRESS **
  ITERATION 4 OF 10

DEVIATION FROM EXPECTED VALUE (% of Max. Units)

TBRGRWTH    0.01 THN'VEST -    0.26 TBRHRVST -    3.60 DR&ELKPD    1.28
D&EHRVST    2.51 WLDFIRES    1.74 WLDRNSS -    1.95 ROADCON    0.99
FORPROD -   0.01 GRAZING -    0.01 H2OYIELD -    0.01 PRESBURN -    0.01
DEVREC -    0.01 DISPREC -    0.01 NEGBEAUT -    0.01 INVSTREC -    0.01
REVCOUNT -  0.01 RINGINVST -    0.01 CLEARCUT -    0.01 PARTCUT -    0.01

```

Figure 4. "Unrefined" (assigned) strength-of-impact parameters.

EZ-IMPACT															
Multiresource Management Model III for the Enchanted Forest															
PROJECT: ENCHF0R3															
Unrefined Model															
No. Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1 TBRGRWTH	.	0.0300	-2.0000	-1.0000	-1.0000	-0.0300	.	.	.	.	.	.	.	.	.
2 THN'VEST	.	.	2.0000	.	.	-1.0000	.	.	.	.	.	.	.	.	.
3 TBRHRVST	1.0000	.	.	.	.	-3.0000	-2.0000	.	.	.	.	.	.	.	.
4 DR&ELKPD	-0.0200	2.0000	1.0000	.	-2.0000	2.0000	.	.	.	.	.	.	.	.	.
5 D&EHRVST	-0.0200	2.0000	1.0000	2.0000	.	.	.	0.0100	.	.	.	.	.	.	.
6 WLDFIRES	0.0100	-2.0000	1.0000	.	1.0000	.	1.0000	-0.0100	.	.	.	.	.	.	.
7 WLDRNSS	.	.	-3.0000	.	.	2.0000	.	-3.0000	.	.	.	.	.	.	.
8 ROADCON	.	.	0.0200	.	.	2.0000	.	.	.	.	.	.	.	.	.
9 FORPROD
10 GRAZING
11 H2OYIELD
12 PRESBURN
13- DEVREC
14 DISPREC
15 NEGBEAUT
16 INVSTREC
17 REVCOUNT
18 RINGINVST
19 CLEARCUT
20 PARTCUT

Figure 5. "Refined" strength-of-impact values, adjusted so that simulated expected values fall within 4% of assigned expected values.

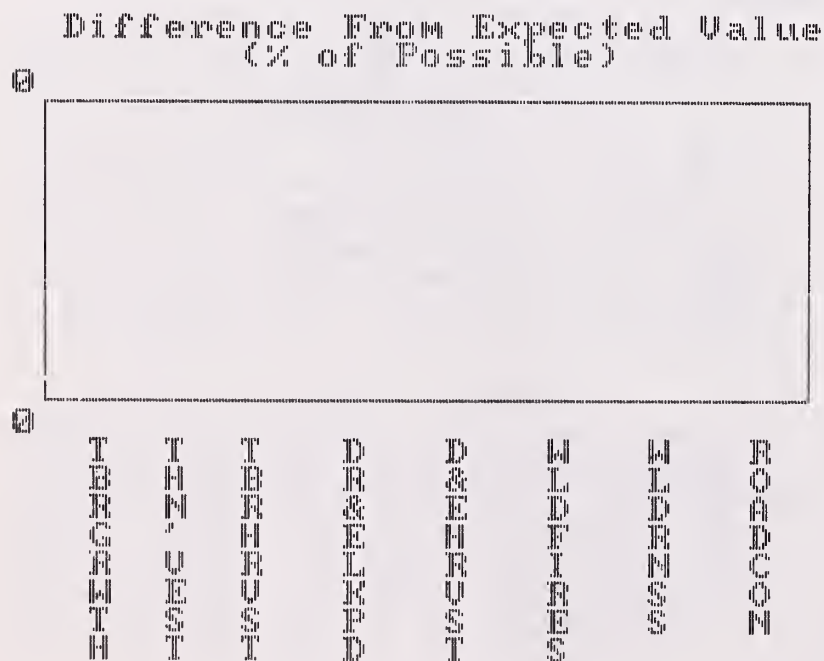
EZ-IMPACT

Multiresource Management Model III for the Enchanted Forest

PROJECT: ENCHF0R3
Refined Model

No. Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1 TBRGRWTH	.	0.1414	-0.7029	-0.6876	-0.2122	-0.0064	.	.	.	.	.	.	.	.	.
2 THN'VEST	.	.	1.6468	.	.	-1.1139	.	.	.	.	.	.	.	.	.
3 TBRHRVST	2.3492	.	.	.	.	-0.7394	-0.8513	.	.	.	.	.	.	.	.
4 DR&ELKPD	-0.0162	2.4655	0.8575	.	-1.6224	2.4655	.	.	.	.	.	.	.	.	.
5 D&EHRVST	-0.0232	1.4191	0.6582	1.5343	.	.	.	0.0071	.	.	.	.	.	.	.
6 WLDFIRES	0.0078	-2.5743	0.9701	.	0.7769	.	0.6362	-0.0129	.	.	.	.	.	.	.
7 WLDNRSS	.	.	-0.8889	.	.	6.7501	-0.8889	.	.	.	.	.	.	.	.
8 ROADCON	.	.	0.0031	.	.	0.3109	.	.	.	.	.	.	.	.	.
9 FORPROD
10 GRAZING
11 H2OYIELD
12 PRESBURN
13 DEVREC
14 DISPREC
15 NEGBEAUT
16 INVSTREC
17 REVCOUNT
18 RNGINVST
19 CLEARCUT
20 PARTCUT

Figure 6. Bar-chart for "EXPECTED" experiment. Refined model generates "zero" deviation from expected values if the simulations fall within 4%.



degree of confidence. The value of building the model, thinking through the important variables in our forest system and how they interact with one another, has been substantial. We have been forced to adopt and to experience a "systems view" in order to get this far, and that much alone, I believe, justifies the exercise.

But now the practice of multiresource forest management can begin. We can design different management alternatives (EZI calls them "experiments") and see what would happen to the system if they were implemented. Suppose we doubled the timber harvest? We might name this "experiment" CLEARCUT, multiply our initial "expected change" value for the TBRHRVST variable by two, and run that simulation.

The impacts on all the other variables are displayed in Figure 8, measured in terms of "Difference from Expected Change." Thus we can compare the proposed alternative to our current management regime. (Again, the data can be printed in tabular form as well.)

Figure 7. Tabular results of running the EXPECTED experiment. Differences from "expected values" are zero, as in the bar-chart in Figure 6.

EZ-IMPACT

Multiresource Management Model III for the Enchanted Forest

EXPERIMENT: EXPECTED

Time period is 5 years, beginning 1/ 1989.

Variable No.	Variable	Initial Value	Final Value	Expected Val	Difference from Initial Value		Difference from Expected Val	
		(% of Max.)	(% of Max.)	(% of Max.)	(%)	(% of Possible)	(%)	(% of Possible)
1	TBRGRWTH	50.0	75.4	75.4	50.7	50.7	0.0	0.0
2	THN'VEST	33.3	60.3	60.3	80.9	40.5	0.0	0.0
3	TBRHRVST	33.3	65.0	65.0	94.9	47.5	0.0	0.0
4	DR&ELKPD	50.0	63.0	63.0	25.9	25.9	0.0	0.0
5	D&EHRVST	50.0	77.4	77.4	54.8	54.8	0.0	0.0
6	WLDFIRES	9.1	15.8	15.8	73.6	7.4	0.0	0.0
7	WLDNRSS	50.0	67.1	67.1	34.3	34.3	0.0	0.0
8	ROADCON	9.1	12.1	12.1	32.6	3.3	0.0	0.0
9	FORPROD	100.0	100.0	100.0	- 0.0	- 0.0	0.0	0.0
10	GRAZING	100.0	100.0	100.0	- 0.0	- 0.0	0.0	0.0
11	H2OYIELD	100.0	100.0	100.0	- 0.0	- 0.0	0.0	0.0
12	PRESBURN	100.0	100.0	100.0	- 0.0	- 0.0	0.0	0.0
13	DEVREC	100.0	100.0	100.0	- 0.0	- 0.0	0.0	0.0
14	DISPREC	100.0	100.0	100.0	- 0.0	- 0.0	0.0	0.0
15	NEGBEAUT	100.0	100.0	100.0	- 0.0	- 0.0	0.0	0.0
16	INVSTREC	100.0	100.0	100.0	- 0.0	- 0.0	0.0	0.0
17	REVCOUNT	100.0	100.0	100.0	- 0.0	- 0.0	0.0	0.0
18	RNGINVST	100.0	100.0	100.0	- 0.0	- 0.0	0.0	0.0
19	CLEARCUT	100.0	100.0	100.0	- 0.0	- 0.0	0.0	0.0
20	PARCUT	100.0	100.0	100.0	- 0.0	- 0.0	0.0	0.0

Other bar charts can display the results of the CLEARCUT alternative in terms of "Final Values" for all the variables, or in terms of "Difference from Initial Values."

Figure 9 shows the results of NOCUT, in which timber harvest has been halted completely. Figure 10 displays

the consequences of ALLWILD, which designates every potential acre as wilderness. NOWILD, the results of which appear in Figure 11, is a timber-beast's dream: timber harvesting and road construction have been driven to their maxima. And BLOWUP, displayed in Figure 12, describes the situation in which the maximum acreage of wildfire impact has been sustained.

Figure 8. Results of simulating the CLEARCUT experiment. Variable #3, TBRHRVST, has been assigned its maximum value of 200%.

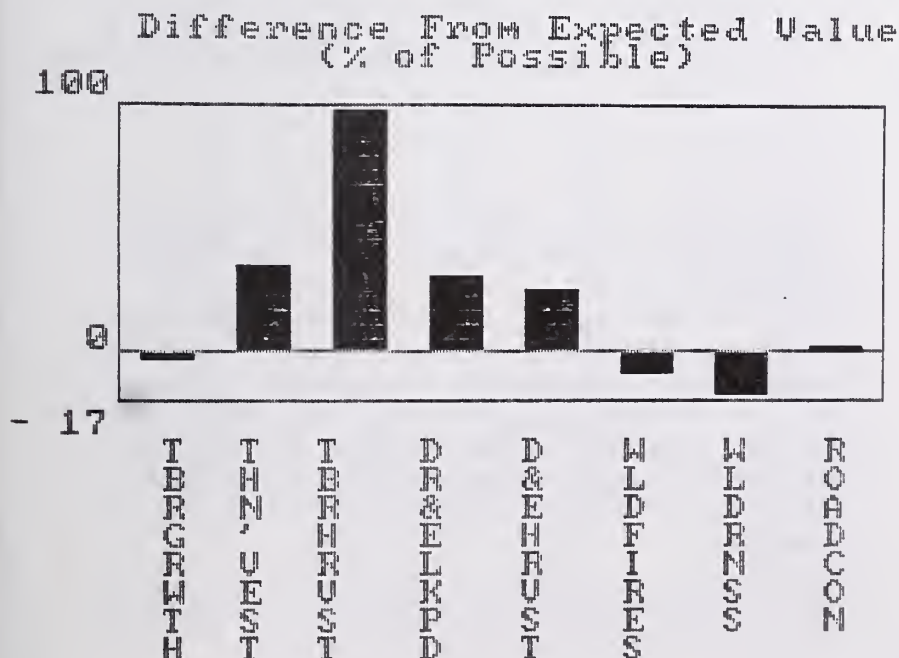
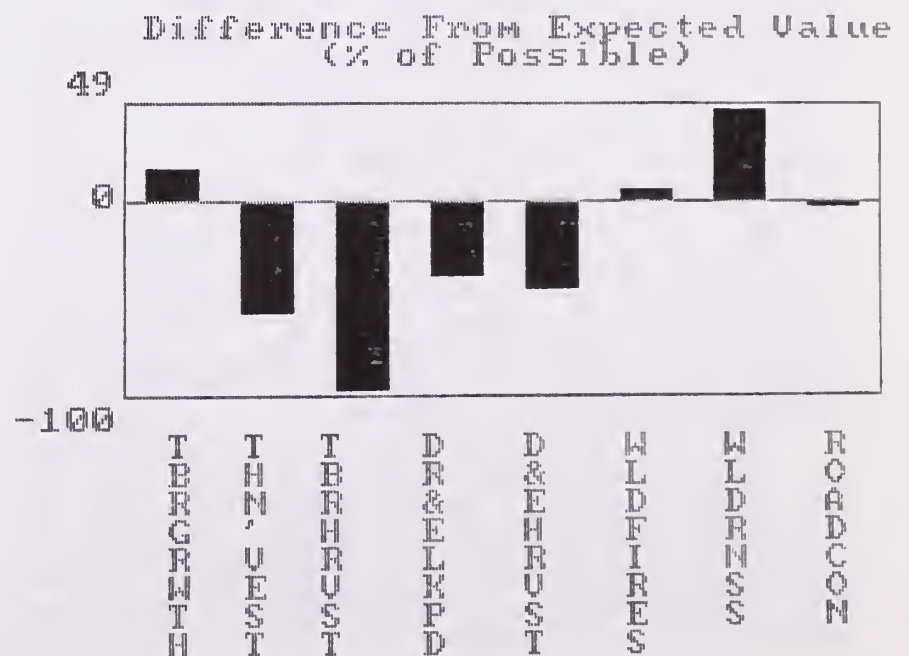


Figure 9. Results of simulating the NOCUT experiment. Variable #3, TBRHRVST, has been decreased by 100%.



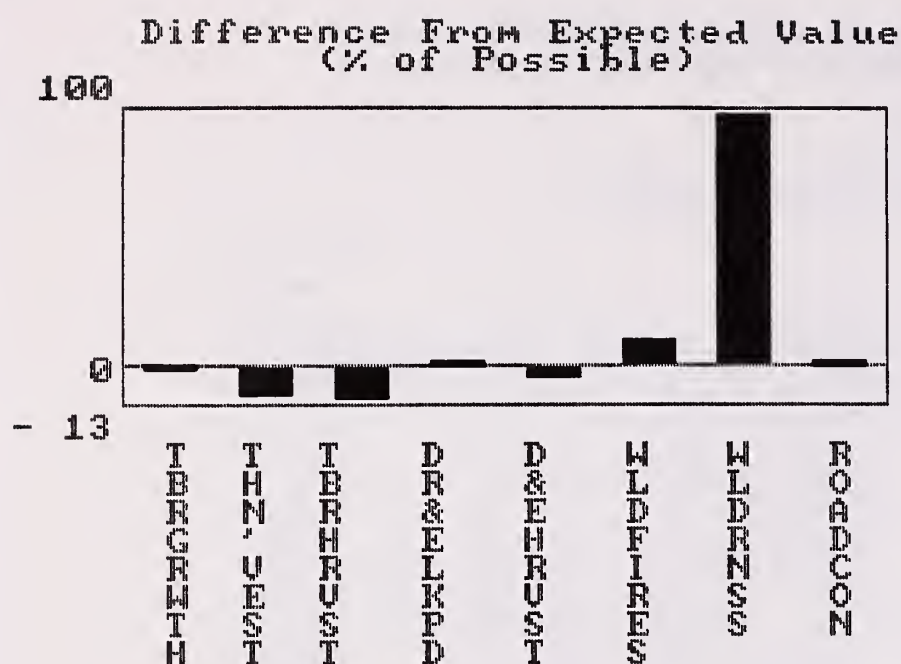


Figure 10. Results of simulating the ALLWILD experiment. Variable #7, WLDNRSS, has been increased by 100%.

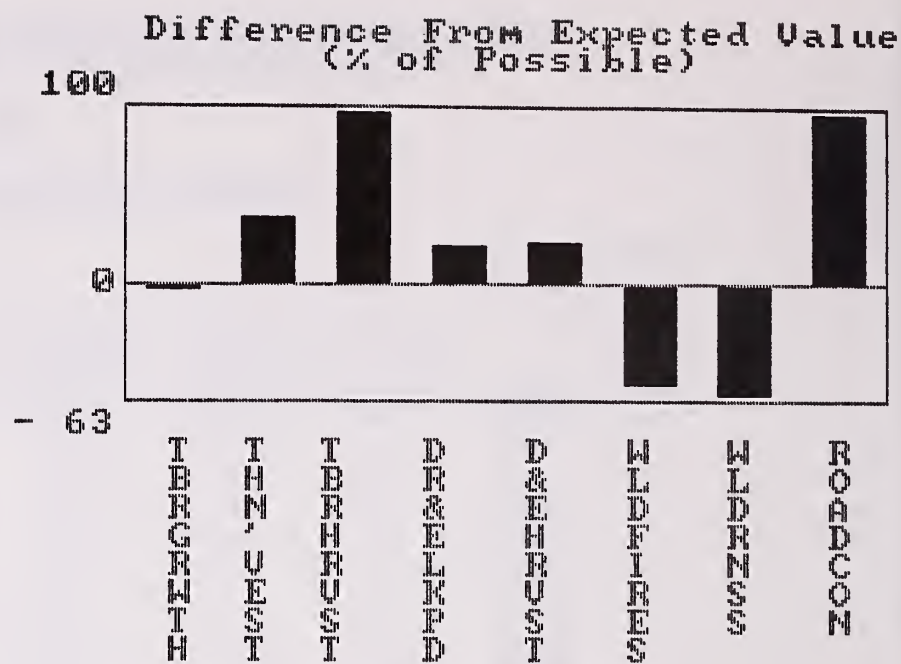


Figure 11. Results of simulating the NOWILD experiment. Variables #3 and #8, TBRHRVST and ROADCON, respectively, have been taken to their maxima, 200% and 1,000%.

Can a manager finally make a choice, using an EZI simulator (or a simulator built some other way), without resorting to an optimizing model as well (or instead)? The affirmative answer to that question is self evident; but in my view, the exclusive use of a simulation model is not only possible, but preferable. (In this case of strategic, not tactical, decisions, that is.)

In comparing the EZI alternatives, or in constructing more and different possibilities in a search for one to apply on the ground, the manager inescapably confronts the expressed and tacit objectives of his management unit. The manager will choose a course of action, one will seem "better" than the others, because it will appear, consciously or otherwise, to further those objectives more than the rejected alternatives. The objectives can be rich, complex, plural, ambiguous, certainly unquantified, even unspecified: in short, the use of simulation models without or instead of an optimization model accommodates reality to a gratifying degree. (There are dangers: the exercise of managerial judgement is difficult, and there are no guarantees. But if managerial judgement cannot be taught, the Harvard Business School is a fraud.)

Optimizers, we have seen, work well on small problems, where indeed the objective can be realistically and legitimately quantified. The final decision is made by the manager, of course, not the model, but optimizers

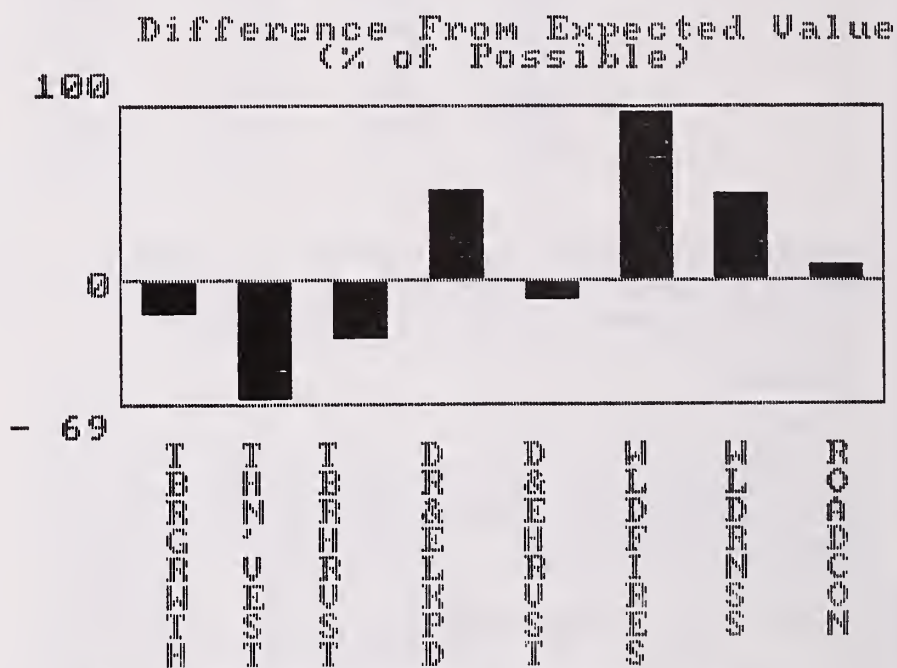


Figure 12. Results of simulating the BLOWUP experiment. Variable #6, WLDFFIRES, has assumed its maximum value, an increase of 1,000%.

challenge only a very primitive mental capability, the process of comparison. Numbers are compared, and one PNV is seen to be larger. The course of action that generates that PNV is thus chosen. This mental activity is precisely equal to the capability of the computer, which is limited to making comparisons, too: it can only distinguish the presence from the absence of an electrical current.

Relying exclusively on a simulator-which I believe is inescapable for

larger, more difficult problems in which objectives can not be realistically or legitimately quantified--calls instead for higher mental capabilities. The manager is called upon to integrate information, not just to compare it, and to make a judgement based on that integration. All a manager needs in order to proceed comfortably is the conviction that his mind--capable of such integration--is indeed superior to the comparison-limited capability of a computer.

So far, only the simulation features of EZI have been exploited, and we have seen the manager operating alone, isolated from the social context in which forestry is practiced. The manager has integrated some information about objectives, which certainly reflects social preferences, but he has avoided direct social interaction.

EZI has another invaluable and ingenious capability to foster such interaction. It can be used to model the social context as well as the biophysical forest. EZI can identify

clientele groups, order their preferences or objectives for each of the modelled variables, and test their resulting levels of satisfaction for any or all of the "experiments," the proposed management alternatives.

My ENCHFOR3 model, implicitly simulating national forest land in the vicinity of Flagstaff, Arizona, contains three clientele groups: the Stone Container Corporation, whose pulp and solid-wood mills collectively are the largest consumer of timber; the Arizona Wildlife Federation; and the Wilderness Society, which has a regional office in Phoenix. (EZI can accommodate up to 15 such groups in a model.) I have also included the multiresource manager as an interested party, to exhibit some important behavior of the EZI software.

Figure 13, which the program prints out, displays the various groups and their respective preferences for the trajectories of each of the modelled variables, which can range from "Up Max" to "Don't Care" to "Down Max." (The dummy variables are assigned the default

Figure 13. Objectives for each variable in the model presumed appropriate for each affected interest group.

EZ-IMPACT

Multiresource Management Model III for the Enchanted Forest

PROJECT: ENCHFOR3

OBJECTIVES

No.	Variable	Group			
		STONECC	AZWLDLF	WILDSOC	MRMGR
1	TBRGRWTH	Up Max 100%	Don't Care	Don't Care	Up 50%
2	THN'VEST	Up Max 200%	Not Down	Not Up	Up 75%
3	TBRHRVST	Not Down	Not Up	Not Up	Up 100%
4	DR&ELKPD	Don't Care	Up Max 100%	No Change	Up 25%
5	D&EHRVST	Don't Care	Not Down	Down 50%	Up 50%
6	WLDIFIRES	Don't Care	No Change	Don't Care	Up 100%
7	WLDNRSS	Down 100%	Not Down	Up Max 100%	Up 50%
8	ROADCON	Down 100%	Not Down	Down 100%	Up 25%
9	FORPROD	No Change	No Change	No Change	No Change
10	GRAZING	No Change	No Change	No Change	No Change
11	H2OYIELD	No Change	No Change	No Change	No Change
12	PRESBURN	No Change	No Change	No Change	No Change
13	DEVREC	No Change	No Change	No Change	No Change
14	DISPREC	No Change	No Change	No Change	No Change
15	NEGBEAUT	No Change	No Change	No Change	No Change
16	INVSTREC	No Change	No Change	No Change	No Change
17	REVCOUNT	No Change	No Change	No Change	No Change
18	RNGINVST	No Change	No Change	No Change	No Change
19	CLEARCUT	No Change	No Change	No Change	No Change
20	PARTCUT	No Change	No Change	No Change	No Change

EZ-IMPACT

Multiresource Management Model III for the Enchanted Forest

PROJECT: ENCHF0R3
EXPERIMENT: EXPECTED

Satisfaction of Group Objectives *

Group	Total Satisfaction (% of Max.):**	Highest Dissatisfaction (%)	Dissatisfaction Variables	Dif. From Initial Val (%)	Objective
STONECC	92	67	WLDRNSS	34.3	Down 100%
AZWLDLF	95	47	TBRHRVST	94.9	Not Up
WILDSOC	87	70	D&EHRVST	54.8	Down 50%
MRMGR	99	13	WLDFIRES	73.6	Up 100%

* Computed using normalized (% of Max.) units.

** Maximum excludes variables assigned 'Don't Care'.

Figure 14. Satisfaction levels of the various interest groups with the EXPECTED experiment, the current management regime.

value "No Change," which is treated with indifference in the simulations.)

Figure 14 compares the various groups' reaction to the current management pattern, the EXPECTED "experiment." Fairly high levels of total satisfaction are indicated for each group, but high levels of dissatisfaction are shown for single variables, reflecting the strong partisanship of the individual groups.

The multiresource manager is virtually 100% satisfied. This "experiment" is, after all, his existing management plan. (His slight dissatisfaction with the WLDFIRES variable is simply a numerical response occasioned by the model-refinement process.)

Similar printouts can be made for each of the "experiments," or the aggregated satisfaction levels can be compared for the entire range of alternatives. Figure 15 does this; we can see, in the right hand column, that one group or another is 100% dissatisfied with each of the extreme alternatives--a conclusion that is intuitively sound.

The existing state of affairs, represented by the EXPECTED "experiment," appears to be the best choice according to any of the decision

criteria. It maximizes the total weighted satisfaction, and is the least

hurtful to all the groups or to any one group, simultaneously. Recalling that the multiresource manager himself (and exclusively) was 100% satisfied with this alternative, perhaps we have displayed a brilliant professional forester performing at his best.

(More likely we have displayed a cagey and fortunate model builder, who designed the array of "expected values" to be as "reasonable" as he could.)

The social-context features of EZI can be exploited a number of ways. A forest management team can "sense" its constituency by role-playing the client groups, for example. Or a formal workshop with representatives from the various groups can fill in the blanks.

Perhaps the most effective (and, unfortunately, expensive) approach is a joint workshop of managers and clients alike. Such a workshop can produce the forest simulator as well as the constituency simulator, and jointly build the inventory of management alternatives. As the simulations are run and discussed, as new alternatives are constructed and tested, consensus comes within reach.

A promising example of this approach was conducted on the Flathead

EZ-IMPACT

Multiresource Management Model III for the Enchanted Forest

Project: ENCHF0R3

Satisfaction of Objectives by Policy Experiment

Experiment	Total Weighted Min. Sat. All Groups (% of Max.)	Total Weighted Sat. All Groups (% of Max.)	Highest Dissatisfaction Any One Group (%)
EXPECTED	[84.4]*	[92.9]**	[69.9]***
CLEARCUT	79.8	91.1	100.0
NOCUT	79.5	89.3	100.0
ALLWILD	83.1	92.3	100.0
NOWILD	72.6	87.6	100.0
BLOWUP	75.9	89.6	100.0

* MAXIMIN Solution: Policy maximizes total weighted minimum satisfaction (i.e., policy is least hurtful to all groups).

** MAXIMAX Solution: Policy maximizes total weighted satisfaction (i.e., policy provides the most benefits to all groups).

*** MINIMAX Solution: Policy minimizes dissatisfaction for any one group (i.e., policy is least hurtful to any one group).

Figure 15. Comparison of the 5 alternate management options ("experiments") in terms of aggregate satisfaction levels.

Literature Cited

National Forest, using an earlier version of the EZI software. (For a description written by two of the participants, see Stout and Brannon, 1989.)

A final feature of EZI is contained in a "Set Priorities" subroutine. Both the variables and the relationships between the variables can be assessed as to their judged importance, ranked, and displayed. This feature is primarily valuable for establishing research priorities. It is an intelligent element in the software, but multiresource managers will find it useful less often than the simulation modelling capability.

EZ-IMPACT™ is a brilliant creation and a compelling product, I believe. Used with care--and with imagination and skill--it can further the application of on-the-ground multiresource management uniquely, immediately, and effectively.

Biosocial Decision System, Inc., 1987. EZ-IMPACT™ The Judgement-Based Systems Modeling and Decision Analysis Program. College Station, Texas.

Brown, Thomas C. and Terry C. Daniel, 1984. Modeling Forest Scenic Beauty: Concepts and Application to Ponderosa Pine. Research Paper RM-256. Fort Collins. Rocky Mountain Forest and Range Experiment Station.

Johnson, K. Norman, 1987. Reflections on the Development of FORPLAN. In FORPLAN: An Evaluation of a Forest Planning Tool. General Technical Report RM-140, USDA Forest Service. Fort Collins. Rocky Mountain Forest and Range Experiment Station.

Stout, Benjamin B. and Edward Brannon, 1989. Participatory Planning; the Flathead Forest Planning Workshop Revisited. NCASI Special Report No. 89-01. New York.

Recreation and Esthetics Management in Southwestern Ponderosa Pine: Assessing Research Needs¹

Merton T. Richards and Terry C. Daniel²

Abstract--Explicit relationships need to be specified between management activities for the production of commodities, and the provision of recreation and esthetics opportunities in southwestern ponderosa pine forests. Models for recreation experience opportunities and forest scenic beauty are reviewed and a combined "expert judgement" model is proposed. Research needs for such a model are assessed.

INTRODUCTION

The recreational use of forestlands in the southwestern United States is increasing rapidly and will continue on this trend for the foreseeable future. Several factors contribute to this trend, some of which are occurring nationally while some are especially prevalent in the Southwest.

Population growth in Arizona and New Mexico has been dramatic for nearly twenty years. Although recent demographic projections indicate some slowing in the rate of growth of the southwestern population the trends are still upward. In addition, people from major population centers in Texas, southern Nevada, and southern California continue to pursue leisure activities in the forested mountains of Arizona and New Mexico in growing numbers.

Rapid technological innovation in leisure oriented equipment and modes of transportation contribute to growth in forest recreation nationally, and the Southwest in particular. Relatively inexpensive, comfortable, easy to use, and readily available equipment for camping, fishing, hunting, skiing, and hiking pervades the marketplace. Motorhomes, small,

but rugged four-wheel drive trucks, boats, and all-terrain vehicles including "mountain" bicycles complement the new equipment in meeting a demand grounded in a popular cultural ethic. Outdoor activities are believed to contribute to peoples' mental and physical well-being and to be socially desirable.

Social and cultural evolution in the United States has resulted in a predominantly urban population that is culturally diverse and somewhat older, on average, than in previous decades. In general, people today enjoy greater economic prosperity and have more options for leisure time, including retirement, than ever before. Among other effects, the "season of use" of forestlands for recreation has expanded to a year long basis. Other effects of social and cultural change, however, are less benign. A greater variety in leisure activity preferences and values, more urban oriented social behavior patterns, and a bigger range in the ages of recreation participants provide complications for forest management.

The growing numbers and diversity of recreation users of forestlands guarantees social and managerial conflicts, both between recreation and other forest uses, and among recreation uses. Even on forestlands presumably devoted exclusively to recreational use, e.g., federal and state parklands, national recreation areas, and designated wilderness areas, certain other uses are provided for, ranging from livestock grazing to spiritual, scientific, and educational purposes. Most forestlands, including private lands, are explicitly devoted to multiple uses.

It is generally assumed that commodity uses of forests are competitive with recreational (amenity) uses, and that commodity production will denigrate recreational opportunities. While

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²Merton T. Richards is Associate Professor in the School of Forestry, Northern Arizona University, Flagstaff, and Terry C. Daniel is Professor in the Department of Psychology and School of Renewable Natural Resources, University of Arizona, Tucson.

THE WILDLAND RECREATION EXPERIENCE

this is often the case, it is not universally true. For one thing, some levels of forest management conducted for the production of commodities can improve recreation opportunities such as better road access, improved wildlife habitat, or increased scenic vistas associated with the removal of forest trees. For another, some levels of recreational activity on forest lands can degrade the potential for commodity production, such as an increased fire hazard, negative impacts on livestock production, or restrictions on off-forest water uses to preserve on-forest water based recreational opportunities.

Within the spectrum of recreational uses of forestlands, many activities are competitive. Activities that depend on solitude cannot take place, obviously, at the same time and place as those recreation pursuits involving large groups of people or that are dependant on motorized vehicles. Hunting and fishing activities typically are inconsistent, at least in the same time and space, with non-consumptive wildlife appreciation.

The problem, in the context of forestland management, is one of accommodation and amelioration. It is necessary to define appropriate trade-offs between and among various forest land uses. To define trade-offs, explicit physical and social relationships for the various uses need to be expressed. It would be useful to model, both quantitatively and qualitatively, response functions that express changes in specific forest recreation opportunities as a function of changes in physical and biological forest characteristics.

This paper will describe and define the forest recreation experience, the relationship of recreation opportunities to common forest management activities, and propose an approach to modeling relationships between recreational and other uses of forestlands. Consideration will be given to the esthetic quality of forestlands, both in its own right and as an important contributor to many forest recreation activities. Research needs will also be defined.

The geographic focus of this paper is on the southwestern United States with particular reference to ponderosa pine forests. This forest type is prominent in Arizona and New Mexico and provides a substantial amount of forest recreational opportunities. Most of the arguments and conclusions made in this paper can be applied to the mixed conifer and pinyon juniper forest types that also occur in this region.

Wildland recreation is a special form of leisure behavior not only because it takes place out-of-doors, but, because it depends upon a natural, or "wildland," environment. Particular environmental conditions, or settings are crucial to the fulfillment of wildland recreation goals, because the wildland recreationist seeks meaningful and satisfying experiences rather than simply engagement in activities.

Importantly, forest recreation takes place in settings that result from forest management actions of one form or another, whether the objective is recreation opportunity, wildlife habitat, or timber harvest, among others. It is unreasonable to assume that any forest management activity will result in appropriate recreation settings, without regard to the way the elements of a setting influence recreation demand and visitor satisfaction. In the following paragraphs, a more detailed examination of settings, recreation demand and experiences, and their relationship to various forest management actions is presented.

Given that different recreation experiences depend upon particular wildland settings, any of a large number of recreation opportunities might be provided through manipulation of the features of a particular wildland area. It is essential for management purposes to define a limited but, reasonable number of desirable experience opportunities. Two considerations are helpful in this regard. Within a particular forest ecotype opportunities for experiences are obviously limited to settings found in that ecotype. Furthermore, no one management entity, including public agencies, is obligated to provide every possible opportunity. The Recreation Opportunity Spectrum (Driver and Brown 1978) provides a methodological framework for assessing and selecting an appropriate mix of wildland recreation opportunities.

The Recreation Opportunity Spectrum (ROS) provides a systematic means to inventory wildland units in terms of recreation opportunity settings, gives a framework for defining management actions appropriate to recreation objectives, and permits the monitoring of impacts due to management over time (Clark and Stankey 1979). The ROS is based on the idea that recreators' pursuits of certain activities in particular places is actually a revelation of their demand for experiences that are satisfying and that may give long term psychological benefits. The focus on experiences rather than activities is central to the ROS concept and it provides a perspective for recreation management that differs from the recent past (Driver and Brown 1978). The ROS model presents a spectrum of experience opportunity classes that relate the range of desirable recreation experiences to an array of possible wildland settings. A key

advantage of the model for managers is the flexibility in the structure of opportunity settings. Setting structure is composed of three components: an ecological component (consisting of biological and physical factors), a social component (the number of people in the setting at one time and their kinds of social interactions), and a managerial component (kinds of facilities provided and the degree of regulation of recreators). Forestland managers can choose to offer any or all possible settings by altering these components. Obviously, the ecological component relates directly to management of wildland resources for non-recreational purposes.

Meeting recreation demand requires forest settings that are consistent with desired experiences. Inconsistent forest settings may arise from management activities that place competing recreational uses in conflict or that introduce incompatible non-recreational uses. When any or all three of the ROS components (ecological, social, managerial) of an opportunity setting do not contribute to a given experience type an inconsistency exists. Whether the inconsistency is important or not is a managerial determination that should be guided by agency or firm goals for recreational use. Therefore, assessing the impacts of management actions on recreational use of forestlands requires a clear understanding of the management entity's goals and responsibilities.

The ponderosa pine forests of the southwestern United States offer settings potentially appropriate for a broad range of recreation experiences. The particular experiences recreators demand is, to a degree, dependent upon economic and demographic characteristics of the southwestern U.S. population. The outstanding feature of this population, especially in Arizona, is growth. Population growth is occurring across most income classes and age groups, but middle income earners and young to middle age groups are favored. It appears that these groups will exert an increasing demand on wildland resources for leisure pursuits. In particular, the ponderosa pine forestlands will continue to be highly valued recreational settings due to relatively easy access, generally high scenic quality, moderate climate, and spacious atmosphere.

The land ownership pattern in the Southwest is dominated by federal acreage, and, the total acreage of land available for wildland recreation opportunities is still very extensive relative to the regional population. This places relatively large, federally managed, wildland recreation opportunity areas in close proximity to rapidly growing urban centers. The result is an increasing number of

recreation visits of short duration (4 hours to 3 days) to federal land locations.

In summary, forestland recreation opportunities in the Southwest will continue to occur on federal lands. This, in turn, means that the supply of opportunities is, at least conceptually, very large. However, specific recreational opportunities associated with ponderosa pine forests are constrained by certain factors.

Southwestern ponderosa pine forests are predominantly managed by the U.S. Forest Service. Obviously, from the foregoing, agency goals coupled with ecological characteristics common to the forest type limit the spectrum of opportunity settings that will be provided. For example, the U. S. Forest Service should provide opportunity settings for experiences that are unavailable under private sector or other public sector management.

RECREATION MANAGEMENT IMPACTS FOLLOWING OVERSTORY MANIPULATION

In general, management impacts on recreation can be either positive or negative and they may result from both non-recreational and recreational activities. The focus here will be on impacts due to non-recreational management activities. The incidence of management impacts on recreation occurs in the consistency of the recreation opportunity settings. Negative impacts create inconsistencies while positive impacts have the opposite effect.

The impacts of timber management activities on recreation primarily affect visibility and access. Roads built for timber management purposes frequently enhance recreational opportunities. For more primitive experiences, however, roads may be a distraction. In any case, timber management roads are not typically located or designed primarily for recreational experiences. As a result, negative impacts on visibility and cognition often occur. For example, more than 75 percent of respondents to a recreation study in the Mogollon Rim area of Arizona wanted no more forest roads (Richards and others 1977). Their concern was for esthetics and wildlife.

Timber harvesting activities can create significant visual impacts due to the scale of operations. Visual impacts of roads take two forms: the scenic quality of the road corridor, as viewed from the road, and the visibility of the road as a more distant landscape feature. The initial, disruptive appearance of harvested areas usually seen from roads or other travel ways, is exacerbated by soil disturbance and slash. On the other hand, small scale or selective harvest activities can serve to improve the scenic quality of forest areas. Far views,

showing incongruent vegetation patterns or road scars provide negative visual impacts. Timber harvest activities may also impact air and water quality, damaging esthetic values and degrading swimming and fishing opportunities. Livestock production in ponderosa pine forests takes place primarily in the summer and early fall seasons. While this is also the period of heaviest recreational use, the negative impacts of livestock production on recreation are mostly indirect involving fixed facilities (fences, buildings, tanks) and induced vegetative changes. On the other hand, the presence of livestock in the forest in common dispersed patterns may contribute a romantic sense of southwestern tradition to wildland recreation experiences.

Vegetative changes induced by livestock grazing can adversely affect scenic values. Severe overgrazing and trampling can lead to soil erosion with resulting visual blight, especially in riparian areas. Alterations in plant species composition, primarily of larger shrubs and forbs can reduce the scenic value of forest lands (Brown and Daniel 1984).

The effects of fire on recreation in ponderosa pine forests are primarily esthetic. Coupled with increasing public awareness of the value of fire in forest ecosystems, recent research shows that negative impacts on scenic quality from forest fires are very short term (Anderson and others 1982). In fact, prescribed burning may reduce slash from timber harvesting or naturally accumulating downed wood and forest litter, improving scenic values.

Taylor and Daniel (1984) show that light burning may improve scenic beauty of forest landscapes over time (their data ranged over five years). Severe burning, however, had a negative impact on scenic value. They also assessed the impact on recreation acceptability by respondents' preferred activity. Campers and picnickers found fire impacts more unacceptable than those interested in nature study.

Efforts to increase water yield in ponderosa pine forests, or to control water run-off can have negative effects on recreation. Physical facilities such as dams and roads associated with water development or control projects can provide visual impacts. Water bodies impounded by these facilities may enhance the landscape view and usually provide for water based recreation. Such impoundments, however, can result in the loss of wild and scenic rivers, and river or stream based fishing opportunities.

For the most part, management of wildland resources for wildlife complements recreation management objectives. The visual quality of

forest scenes is generally improved by diversity in resource conditions, especially vegetation. This is consistent with the provision of wildlife habitat for a broad array of forest fauna.

Particular recreation experiences may be precluded in locations where wildlife are sensitive to human contact or to certain recreational activities. Some forms of off-road vehicle use are incompatible with wildlife requirements as are some forms of fishing. Threatened or endangered species merit special consideration in this regard. These impacts on recreation are mitigated to some degree by the value many recreators hold for knowing that wildlife is protected (Witter and others 1978; Richards and others 1979).

Insects and diseases occurring in forest areas bring negative impacts on recreators by defoliating, killing, or grossly deforming vegetation. Less often, insects may create impacts when they act as pests to recreators. However, they serve a useful function as a food source for wildlife and as agents of decomposition of residues and waste matter, thereby creating more attractive and healthy recreation settings.

MODELING RECREATION AND ESTHETICS

It has been a common assumption that forest recreational and esthetic resources are not amenable to systematic, much less quantitative, analysis. The assumption seems rooted in the notion that recreation and esthetic experiences are dependent upon highly subjective attitudinal and emotional responses. However, commonalities in recreational choices (as evidenced by crowding of popular sites) and consistency in expressions of esthetic quality have frequently been identified. As a result, systematic and even quantitative assessments of the quality of forest recreational and esthetic experiences have been accomplished.

Wildland recreation and esthetic appreciation interests are only two of an extensive array of resources and uses that must be provided by limited forestlands. An understanding of the relationships between recreational, esthetic and other important uses is essential to effective forest management. To the extent that these relationships can be defined explicitly, and where possible, quantitatively, better management decisions for forestland uses can be made. In this paper the intent is to employ the Recreation Opportunity Spectrum concept in a proposed model to systematically define the relationship between characteristics of forest environments and the opportunities for recreational experiences that visitors seek. Further, models of forest scenic beauty will be reviewed and related to the proposed recreation model.

The ROS is typically defined as a functional linkage between recreational experience opportunity classes and a variety of environmental settings, or forest conditions. An opportunity class is a subjectively defined segment of the opportunity spectrum. It defines a class of recreational experiences that could be enjoyed in a particular environmental setting. The setting, in turn, varies according to its ecological, social, and managerial attributes. Therefore, changes in the environmental setting will result in changes in recreation experience opportunities.

Recreation Models

Recreation models have been developed for a wide range of purposes, from simulating visitor distribution across proposed sites (Cesario 1975), to forecasting use (Stynes 1983), and simulating dynamics of use over time (Levine and Lodwick 1983), to numerous economic demand models (Ward and Loomis 1986; Sorg and others 1984; Walsh and others 1989). The ROS is a model of recreation supply, at least as it has been described in this paper. While models describing the use of, or demand for, recreation are fairly common, models of recreation supply are less so, probably because of a general assumption that wildland recreation largely takes place in environments unmodified by humans, and, therefore, the appropriate supply is fixed. As Clark and Stankey (1979) point out, this is too simplistic. The ROS, in fact, can be used as an analytical tool to evaluate the impact on the supply of recreational opportunities due to human use of forest environments. The simulation of forest environments affected by management actions should include changes in the spectrum of recreational opportunities (supply) defined by the ROS.

Implementation of the ROS has been done by the U.S. Forest Service. In their approach, they have defined six recreation experience opportunity classes. Further, they provide descriptive statements for each class that characterize the setting (or forest environment) and the kinds of experience provided by each class. However, these characterizations are general and remain somewhat vague.

The Forest Service has developed specific criteria to be used to delineate classes according to the ROS characterizations. The criteria specific to the ecological component of an environmental setting are remoteness, measured in miles from roads or other vehicle access, size in acres, and evidence of humans as noted by man-made features. The social component of a setting is assessed by a user density criterion, measured in the frequency of encounters with other parties. The criteria

used to define the managerial component are the degree of regimentation and how noticeable it is.

These criteria permit relatively unambiguous standards and management guidelines to be developed for a forestland area. ROS classes can be delineated and mapped for the area, and management prescriptions for both recreational use and for other forest resource uses can be developed by ROS land class.

The ROS model should permit a rational and optimal allocation of land to a mixture of appropriate recreational uses as well as other land uses. That is, for a given land class the model should help determine the amount and quality of recreational experiences gained or lost in exchange for gains or losses in non-recreational or competing recreational uses.

Presumably, changes, through use, in ecological, social, or managerial components of settings that would alter the ROS class delineation could be identified and stopped if deemed necessary. Clark and Stankey (1979), however, point out the potential for "inadvertent inconsistencies" to develop in ROS classes as a result of subtle, incremental, and cumulative changes in setting components. A simple example might be an improvement in access to an area that is consistent with the ecological component of a setting, but that encourages greater recreation use resulting in an inconsistent social component for the setting.

Stankey and others (1985) have proposed a refinement to the ROS model known as the Limits of Acceptable Change (LAC). They propose a nine step process for implementing the ROS in wilderness areas in which specific resource and social conditions that are desirable, achievable, and measurable are defined. The process includes steps to specify indicators of resource and social conditions, standards for resource and social indicators, and to monitor the indicators and conditions for change. Managerial actions can be designed to halt or promote change according to management goals.

The steps permit the identification of critical biophysical indicators of potential change in ROS class delineations. It would be a useful addition to the ROS model to adapt several of the LAC steps to the ROS analysis of all forestland areas (not just wilderness areas). In particular, LAC adds a dynamic, temporal feature to the ROS model. The monitoring step is tied directly to specified indicators and standards of change. However, the explicit linkages between various biophysical and social conditions and the kind and quality of different recreational experiences remains judgemental. Until the linkages are known with greater certainty and consistency, expert opinion can be used to approximate the exact relationships.

Rauscher (1987) provides some definitions of an "expert system." To paraphrase, expert systems are a subfield of artificial intelligence. They employ knowledge and inference procedures to solve problems. They are designed to mimic human reasoning processes that depend upon a knowledge base provided by human experts. Application of the ROS to ponderosa pine forests by "expert" foresters, recreation specialists, and landscape architects can provide a useable knowledge base. Fairweather (1987) generally describes an expert system computer shell called RuleMaster. This system is rule-based. That is, it employs a procedural decision process analogous to a decision tree. The procedure is based on rules, or declarative knowledge, supplied by experts. Given a set of related, declarative facts (stimulus), conditional "if, then" arguments are formed, proceeding stepwise toward a solution (response).

Following a suggestion by Jubenville and others (1986), a simulation model framework can be conceived that simulates biophysical responses to management actions. These authors describe a framework designed to assess wildlife habitat impacts resulting from economic development. They note, also, that a parallel application could be made for the ROS.

Using the six opportunity classes defined by the Forest Service, an Opportunity Class Index (OCI) can be formed. The OCI could range from one to six, an arbitrary scale representation of the ROS. That is, an OCI of one would represent a primitive ROS opportunity class and an OCI of six an urban class. When multiplied by a geographic measure, such as acres, a "quantitative" measure of recreation potential for a forestland area results. Subjectively determined gradations between one and six would represent the spectrum of opportunities, by geographic sub-area, for a forest area at a point in time. This output could be measured as Experience Opportunity Units (EOU's) by ROS class. EOU's in a given class would be weighted by the inverse of the OCI for that class to make EOU's across classes equivalent. Changes in EOU's over time would reflect the variable responses to management stimuli.

The relationship between recreation opportunity classes and the ecological, social, and managerial components must be expanded to allow for the subjective determination of the OCI. Six mutually exclusive environmental conditions are postulated for the model that result from specific combinations of biophysical (ecological), social and managerial components. Each component can take on a value of 0 or 1. The values of components for an environmental condition are multiplied and then weighted, progressively by thirds, from 0.333

for Environmental Condition I to 2.000 for Environmental Condition VI.

LAC-type indicators, as defined by standards, are used to make a qualitative suitability assessment of each component for an Environmental Condition on a scale of 0 or 1. Implied in the relationship between indicators and the assessed value of the components are linear, or non-linear mathematical relationships. However, the complexity of these relationships presents a formidable task for modeling them with explicit mathematical functions. An initial approximation can be derived by developing a system of relationships based on expert judgments.

RuleMaster is one example of a system shell that might be employed to provide EOU's. The shell could be coupled with forest simulation models for overstory or other biophysical, social, or managerial indicators of change. As indicators change under various simulated conditions, EOU's by ROS class can be determined.

Scenic Beauty Models

A number of different approaches have been developed for assessing the scenic beauty or scenic quality of landscapes. Each approach adopts or implies a somewhat different concept or definition, but each may be traced to the concerns expressed in environmental protection legislation of the 60's and 70's for "natural scenic beauty." Daniel and Vining (1983) and Zube and others (1982) present reviews of methods and conceptual bases for the major approaches, along with discussions of the advantages and disadvantages of each. This section will focus on what both reviews identified as the "psychophysical approach" as exemplified by the Scenic Beauty Estimation or SBE method introduced by Daniel and Boster (1976).

The SBE method is a system for measuring and modeling landscape esthetics, based on the perceptual judgements of human observers. Observer panels, usually of 30 or more people, are typically sampled from the general public or from some other population of interest. The SBE method is an adaptation of classical psychological methods developed by psychophysicists around the turn of the century. It relies on concepts and procedures developed by Thurstone (1927), and described in detail by Torgerson (1958) with some extensions developed by signal detection theorists such as Green and Swetts (1966).

Most of the research in landscape assessment has relied on photographic representations of the assessed landscapes. The remoteness of many of the areas for which assessments have been required, such as forests, wilderness areas and other wildlands, has made

the costs of having adequate numbers of observers sampled from the public directly view these areas prohibitive. A further inducement for the use of photographic representations is the difficulty of achieving adequate experimental control in actual field settings (as in the order of presentation and the observation/judgement context). The use of photographs as surrogates for actual landscape/environments raises several issues having to do with the validity of such representations. One concern, for example, is with determining which of the very large number of potential scenes available in a forest area should be selected to represent that area. Another concern is that pictures may not convey all that is potentially important to human aesthetic response to landscapes.

A number of studies have systematically addressed the issues that arise in using photographic surrogates in landscape assessment. View sampling procedures, photographic quality requirements, and viewing context have all been studied. The results from a large number of studies (Daniel and Boster 1976; Kellomaki and Savolainen 1984; Shafer and Richards 1974; Stewart and others 1984) have agreed that scenic beauty assessments based on appropriately sampled and presented color photographs (typically projected color slides) are consistently very closely correlated with assessments of the same areas when viewed and judged directly on site.

As with all psychophysical procedures, some overt indicator response must be selected; i.e., the observer must overtly indicate which landscape is preferred, or judged to be of higher scenic beauty. For landscape assessment applications, indicator responses have ranged from rather simple paired-comparisons to more complex magnitude estimation procedures.

The SBE method has typically employed a categorical rating scale procedure coupled with transformations consistent with Thurstone's (1927, 1959) "Law of Categorical Judgement." Observers are required to independently rate the scenic beauty represented by each of a number of landscape scenes using a 10-point scale, where a 1 on the scale indicates very low scenic beauty and a 10 very high scenic beauty. The rating procedure was found in studies by Daniel and Boster (1976) and by Buhyoff and others (1982) to yield perceived scenic beauty scales (after appropriate transformations) that were empirically very similar to those produced by paired-comparison procedures.

At the current time, the psychophysical approach to scenic beauty assessment has essentially converged on the use of systematically sampled photographic representations of the assessed landscapes and

categorical rating scales for the response indicator.

The scenic beauty assessment procedures described above represent only the first component of the psychophysical approach. The second component is the specification of the relationship between the scenic assessments and the physical features of the assessed landscapes. Early efforts in this regard relied on relatively simple correlation methods (Daniel and Boster 1976). More recently, multi-variate statistical techniques, in particular multiple regression analysis, have been employed (Arthur 1977; Buhyoff and others 1982; Brown and Daniel 1984; Schroeder and Daniel 1981; Schroeder and Brown 1983).

Scenic beauty models developed within the SBE approach have generally been based on directly measured "manageable features" of the landscape. That is, the perceived scenic beauty indices, SBEs, for a set of landscapes are related to objectively measured features of those landscapes, such as the number and size of trees, the amount of grasses and other vegetative ground cover and the volumes of down wood on the forest floor.

The particular physical characteristics selected as independent variables for the SBE models were chosen because they are the variables that are typically measured (inventoried) and manipulated in the context of forest management; a major goal of the SBE method was to be able to inform forest managers of the scenic implications of various management actions. Also, it has become increasingly common practice in forest planning to make management decisions based on explicit quantitative predictions of expected changes in forest characteristics. Predictions are generally made by a set of computer implemented environmental simulation models that project changes in the biological components of the forest based on modeled management actions and/or natural events such as insect infestations, drought, fire or ecological succession. Thus, the ability to link projected changes in the biological features of the forest landscape to changes in perceived scenic beauty is essential if "natural scenic beauty" is to play an appropriate, congressionally mandated role in the management of the nation's forests.

Daniel and associates (Arthur 1977; Brown and Daniel 1986; Schroeder and Daniel 1981; Schroeder and Brown 1983) have developed a number of models that are applicable to southwestern ponderosa pine forests. While a number of assessment studies have been done, there are not yet any SBE models available for mixed conifer, spruce fir or other important forest types.

All of the above models have been developed for predicting scenic beauty in the context of the "near view" perspective, i.e., for viewing

situations in which the viewer is within the forest canopy and where views are generally restricted to a few hundred feet. Further, most of the forest areas modeled in this way have been either essentially natural, undisturbed areas or areas where human disturbance (e.g., timber harvest) was sufficiently in the past that the area had recovered to a relatively stable state and appeared undisturbed. Brown and Daniel (1984) investigated recently harvested ponderosa pine stands and found that "pre-harvest" models were not good predictors of immediate post-harvest forest stands. They were not, however, able to develop adequate post-harvest models with the limited data set that was available for their study. Given the goal of being able to project the scenic consequences of various forest management alternatives, there is clearly a need for the development of post-disturbance (especially timber harvesting) scenic beauty models.

Near view perspectives are important in many forest areas, representing views frequently experienced by hikers, campers, picnickers and those driving along forest roads. However, more expansive views of the forest landscape, as from overlooks that provide views over large areas of forest, are often much more important. Indeed, these "vistas" are probably what most often comes to the mind of the public when reference is made to "forest scenic beauty," and has been the primary concern of the forest landscape architects' expert assessment systems. Efforts to quantitatively model vista scenic beauty have been somewhat more restricted, and substantially less successful, than the near-view models. Perhaps the earliest efforts were those of Shafer and his associates (Shafer and Meitz 1970; Shafer and Richards 1974). In these studies scenic beauty rankings were related to measures of features of photographs of landscape scenes such as the perimeter of various vegetation types in different locations on the photograph.

Both the early Shafer studies and the later efforts by Buhyoff found that variations in vista scenic beauty judgments could successfully be accounted for by measures of the composition of the landscape scene taken from photographs. A serious limitation of these models, however, is that the independent variables are based on picture-plane measurements made from photographs (e.g. "perimeter squared" of foreground vegetation). While it has been shown that these measures are related to perceived scenic beauty indices based on observers reactions to the pictures, it is unclear how these picture variables are related to the bio-physical characteristics of the landscapes represented in the pictures. This is an essential relationship if these vista models are to help project the scenic

consequences of forest management actions that are to be implemented on the ground. There is, then a clear need for further development of vista scenic beauty models that can be more directly related to, or based on, bio-physical features of the forest landscape.

THE RELATIONSHIP OF SCENIC BEAUTY TO RECREATION MODELING

Conceptually, forest scenic beauty is a component of a total recreation experience. The visual quality of a recreation environment is important, among several reasons, because people simply enjoy the natural beauty of forest scenes, and because the appearance of a recreation environment provides an indication of congruity with desired experiences. In other words, for forestland recreation the appearance of a place determines, in part, its suitability for certain activities or experiences. Visual quality is, however, only a part of the experience, and, presumably, varies with different activities and experiences. For example, activities involving tests of skill, such as fly-fishing or white water kayaking may be less dependent on the attractiveness of the surrounding scenery than more contemplative experiences such as picnicking or hiking.

Recent studies directed at assessing the relationship between forest scenic beauty and the quality of recreation experiences suggest that the scenic beauty of the surrounding forest is an important contributor to the value of the experience, as measured in economic terms. However, the value of recreation experiences, even in specific settings, is apparently affected by more than the biophysical elements; facilities and social conditions affect experience values as well (Brown and others 1988, Daniel and others 1989).

In any case, although forest scenic quality is relatively important to the recreation experience it is but one of a host of contributing factors. Models of scenic beauty, therefore, would logically be subroutines to a more general recreation experience model. The forest scenic beauty models developed for near view quality estimation (SBE) are explicitly related to biophysical factors of the forest environment.

Forest scenic beauty models, then, are potentially useful mechanisms for delineating ROS classes in terms of the appearance of the biophysical component of each class. It is not clear, however, at this time, how scenic beauty based models might vary with different experiences or activities. It is reasonable to assume, at least, that the same biophysical factors that contribute to scenic beauty would be indicators of change in the LAC process of monitoring ROS class integrity.

Another way to conceive of a modeling relationship between scenic beauty models and general forest recreation models is with a parallel configuration. Scenic beauty models could be incorporated into simulation routines, and used to generate simultaneous output with an ROS based model, also driven by the same simulation routine. ROS classes would be delineated by area over time along with an assessment of scenic beauty for the same areas.

SUMMARY OF RESEARCH FINDINGS AND FUTURE NEEDS

The literature on recreation and esthetics research, as discussed throughout this paper, shows that the findings are generally tentative, and in some cases inconclusive. This is attributable to the relative recency of a formal and systematic investigation of relationships between natural resource based causal factors and desired wildland recreational outcomes or situations. The findings, nonetheless, are impressive. The ROS concept is a major simplification, but apparently useful model, of a very complex sociopsychological relationship to the natural environment. Still, explicit response functions, with known variables and parameters, remain to be fully expressed and verified.

The simulation model framework for recreation presented in this paper provides a non-specific expression of relationships among stimulus and response variables in the production of recreation experiences. As an initial approximation to specific relationships the judgement of experts is proposed to express the functional parameters of the expected relationships. The variables critical to the relationships have been hypothesized in research activities, but not definitively estimated.

Near view scenic beauty models are more clearly defined in terms of critical variables and parameters. The relationship between measurable biophysical forest characteristics and the perceived scenic quality of forest conditions has been statistically defined. The addition of a temporal component to near view scenic models is still needed, but the causal factors affecting changes in scenic beauty over time should be among the critical biophysical factors already determined for these models. The extensive research accomplishments reviewed in the section on scenic beauty modeling reveal well developed models for the near view. Far view scenic models need to be further developed and refined. In this case, however, the important causal factors remain to be clearly specified.

The recreation and esthetic research accomplished to date clearly suggests the

general natural or biophysical characteristics that must guide future research into the biophysical component of recreation settings. Forest overstory vegetation condition, including density of tree stocking, crown closure, species composition, and age classes is an important aspect of the biophysical component of a forest recreation setting. In turn, overstory condition affects understory vegetation. Scenic beauty models, at least, reveal that understory vegetation has a significant positive influence on forest scenic quality. Riparian conditions, especially with lakes or streams, enhance most recreation settings. Major geologic features also are believed to contribute to recreation experiences.

Much less is known about particular aspects of the social and the managerial components of recreation settings. Research is needed on the desired sociability levels for specific recreation activities. Similarly, the appropriate levels and types of regimentation for different recreation activities or experiences need to be determined.

Near view forest scenic beauty models can be improved by the specification of variables that reflect changes in scenic quality following major alterations in biophysical conditions of settings. Post-timber harvest or post-fire conditions are common in forest settings. It would be useful to determine measurable vegetative conditions that mitigate detrimental effects to scenic quality due to major changes in biophysical conditions. Also, methods to evaluate such changes on the perceived scenic value of far view, or vista, scenes need to be developed. Far view scenes, by their nature, are much more complex, containing many more factors, beyond commonly measured forest elements, than near view scenes. This makes them less tractable for modeling the significant management stimulus variables that contribute to the quality of the scene. In many cases, the significant factors affecting the quality of far view scenes such as weather effects or mountainous terrain, are beyond human control. In southwestern ponderosa pine forests, however, where terrain is generally flat, far view scenes are less complex and often relatively unimportant. It would be useful to know how important far view scenes are in the management of ponderosa pine forests.

Another emerging technology that promises to be very useful in the assessment and modeling of forest scenic beauty, especially for vista landscapes, is based on digital image processing and "paint program" technology that has recently become available and easier to use on micro-computer systems. The basic approach here is to photograph and digitize individual forest scenes, and then to use image processing software to modify features of the scene. Once the image is digitized, special image processing, paint and cut-and-paste routines can be used to manipulate

the image. For example, selected trees in a forest scene can be changed in color (to simulate defoliation or other damage), removed altogether, or replaced by other trees "cut" from other parts of the scene or from another digitized scene (Orland, In press).

A key advantage of digital image processing procedures is that very realistic representations are achieved; the resolution and color quality of the manipulated images are comparable to that of standard color television. Most importantly, however, the digital image processing technology offers a means to experimentally manipulate specific features of a landscape scene while other features are held constant. The realism and flexible feature manipulation capabilities of digital image landscape simulations make this approach most suitable for investigations of public landscape perceptions. The digital image approach offers a very powerful new means for testing and extending scenic beauty models in both near-view and vista contexts. This new technology will undoubtedly play an increasingly important role in future scenic beauty assessment and modeling research.

Initially, a research effort focussed on the validity and reliability of the expert opinions employed in the proposed ROS-based, expert judgement system model should be undertaken. Using the experience setting descriptions developed by the Forest Service, expert opinions would be used to develop decision criteria for the model. Application of the model (simulation) could be undertaken on several geographic locations to test the sensitivity of the procedure and the validity of the judgements. Reliability of the model, as measured by its utility in numerous diverse geographic locations within the southwestern ponderosa pine type could also be determined. Refinement of the model in this manner will lead to more complex research needs for the specification of precise relationships between recreation setting components and experiences.

Eventually, specific indicators of biophysical, social, and managerial conditions must be ascertained, along with standards by which changes in conditions can be measured. For example, to what degree is human influence on the biophysical component of a recreation setting evident to most recreators? Can vegetative succession following human intrusion into natural environments obscure the efforts sufficiently to provide primitive recreational experiences? What level of human intrusion would provide a roaded natural setting for recreation?

Similar questions can be posed for the social and managerial components of recreation settings. The objective of the research endeavor in each case should be to identify

measurable indicators that serve to define a recreation experience class. Those indicators critical to the class definition could then be selected. For example, important biophysical indicators for the semi-primitive, motorized experience class might be tree spacing, essentially undisturbed understory vegetation, and non-maintained roadways. Corresponding social and managerial indicators could be contact with a maximum of three other parties per day, and no regulatory signs, respectively. Such measurable indicators permit standards to be specified by which changes in condition can be assessed. Continued research into social carrying capacity and the psychological satisfaction derived from different settings is necessary.

Research into the relationship between forest scenic beauty models and ROS based models would logically follow from the research efforts described above. How important is scenic quality to different recreation experience classes? Does the assessment of scenic beauty of a forest setting help to define that setting's experience class? More exactly, are the critical biophysical indicators for scenic beauty models the same as those that help define a recreation experience setting?

LITERATURE CITED

- Anderson, Linda M., Daniel J. Levi, Terry C. Daniel and John H. Dietrich. 1982. The esthetic effects of prescribed burning: A case study. USDA Forest Service Research Note RM-413, 5p. Fort Collins, Colorado.
- Arthur, Louise M. 1977. Predicting scenic beauty of forest environments: Some empirical tests. *Forest Science* 23(2):151-159.
- Brown, T.C., and T.C. Daniel. 1984. Modeling ponderosa pine scenic beauty: concepts and application to ponderosa pine. USDA Forest Service Res. Pap. RM-256, 35p. Fort Collins, CO.
- Brown, T.C. and T.C. Daniel. 1986. Predicting scenic beauty of timber stands. *Forest Science* 32(2):471-492.
- Brown, Thomas C., Terry C. Daniel, Merton T. Richards, and David A. King. 1988. Recreation participation and the validity of photo-based preference judgements. *Journal of Leisure Research* 10(4):40-60.
- Buhyoff, Gregory J., J. Douglas Wellman, and Terry C. Daniel. 1982. Predicting scenic quality for mountain pine beetle and western spruce budworm damaged forest vistas. *Forest Science* 28(4):827-838.

- Cesario, F.J. 1975. "A simulation approach to outdoor recreation planning." *Journal of Leisure Research* 7:38-52.
- Clark, R.N., and G.H. Stankey. 1979. The recreation opportunity spectrum: A framework for planning, management, and research. USDA Forest Service General Technical Report PNW-98. Portland, OR.
- Daniel, Terry C. and Ron S. Boster. 1976. Measuring landscape esthetics: The scenic beauty method. USDA, Forest Service Research Paper RM-167, 66 p. Fort Collins, CO.
- Daniel, Terry C., Thomas C. Brown, David A. King, Merton T. Richards, and William P. Stewart. 1989. Perceived scenic beauty and contingent valuation of forest campgrounds. *Forest Science* 35(1):76-90.
- Daniel, T.C. and J. Vining. 1983. Methodological issues in the assessment of landscape quality. p. 39-84. In: *Behavior and the Natural Environment*. Vol. 6. I. Altman and J.S. Wohlwill, eds. Plenum Press, New York. 346 p.
- Driver, B.L. and Perry J. Brown. 1978. The opportunity spectrum concept and behavioral information in outdoor recreation resource supply inventories: A rationale. In: *Integrated inventories of renewable natural resources*. USDA Forest Service General Technical Report RM-55: pp. 24-31.
- Fairweather, Stephen E. 1987. RuleMaster: Experience with building forestry advisory systems. *The Compiler* 5(5):36-38.
- Green, David M., and John A. Swetts. 1966. Signal detection theory and psychophysics. 455p. John Wiley and Sons, New York, N.Y.
- Jubenville, Alan, Scott C. Matulich and William G. Workman. 1986. Toward the integration of economics and outdoor recreation management. *Agricultural and Forestry Experiment Station, Bulletin 68*. School of Agriculture and Land Resources Management, University of Alaska-Fairbanks. 31p.
- Kellomaki, S. and R. Savolainen. 1984. The scenic value of the forest landscape as assessed in the field and the laboratory. *Landscape Planning*, 11:97-107.
- Levine, Ralph L. and Weldon Lodwick. 1983. Continuous simulation methodology: A system dynamics approach to planning, forecasting, and analysis of recreation usage. In: *Recreation Planning and Management*. Lieber, Stanley R. and Daniel R. Fasenmaier, editors. Venture Publishing, State College, PA. pp. 162-185.
- Orland, Brian. In Press. Sound as an information source in landscape perception. *Environment and Behavior*.
- Rauscher, H. Michael. 1987. Expert systems for natural resources management. *The Compiler* 5(5):19-27.
- Richards, Merton T., David A. King, and William B. Kurtz. 1977. Recreational visitors to the Mogollon Rim area. National Technical Information Service, U.S. Dept. of Commerce, No. PB268128/AS. 88p.
- Richards, Merton T., William W. Shaw, Daniel J. Witter, and David A. King. 1979. Resource policy implications of nonconsumptive wildlife enthusiasts visiting southeastern Arizona. Paper presented at the annual meeting of the Arizona-Nevada Academy of Science, April 13-14, 1979. Tempe, AZ.
- Schroeder, Herbert W., and Thomas C. Brown. 1983. Alternative functional forms for an inventory-based landscape perception model. *Journal of Leisure Research* 15(2):156-163.
- Schroeder, Herbert W., and Terry C. Daniel. 1981. Progress in predicting the perceived scenic beauty of forest landscapes. *Forest Science* 27(1):71-80.
- Shafer, Elwood L., Jr., and James Meitz. 1970. It seems possible to quantify scenic beauty in photographs. USDA Forest Service Research Paper NE-163. Upper Darby, PA. 12p.
- Shafer, Elwood L., Jr., and T.A. Richards. 1974. A comparison of viewer reactions to outdoor scenes and photographs of those scenes. USDA Forest Service Research Paper NE-302. Upper Darby, PA. 26p.
- Sorg, Cindy, John Loomis, and Dennis Donnelly. 1984. Net economic value of cold and warm water fishing in Idaho. USDA Forest Service, General Technical Report, RM-107. Fort Collins, CO.
- Stankey, George H., David N. Cole, Robert C. Lucas, Margaret E. Petersen, and Sidney S. Frissell. 1985. The limits of acceptable change (LAC) system for wilderness planning. USDA Forest Service General Technical Report INT-176. Ogden, UT. 37p.

- Stewart, T.R., P. Middleton, M. Downton, and D. Ely. 1984. Judgements of photographs versus field observations in studies of perception of the visual environment. *Jour. Environmental Psychology* 1614(4):283-302.
- Stynes, Daniel J. 1983. An introduction to recreation forecasting. In: *Recreation Planning and Management*. Leiber, Stanley R. and Daniel R. Fessenmaier, editors. Venture Publishing, State College, PA. Pp. 87-95.
- Taylor, Jonathon G., and Terry C. Daniel. 1984. Prescribed fire: Public education and perception. *Journal of Forestry* 82(6):361-365.
- Thurstone, L.L. 1927. A law of comparative judgement. *Psychological Review*. 34:278-286.
- Thurstone, L.L. 1959. The measurement of values. University of Chicago Press, Chicago, IL. 322p.
- Torgerson, W.S. 1958. Theory and methods of scaling. John Wiley and Sons, New York. 460p.
- Walsh, Richard G., Frank A. Ward, and John P. Olienyk. 1989. Recreational demand for trees in national forests. *Journal of Environmental Management* 28:255-268.
- Ward, F.A., and J.B. Loomis. 1986. The travel cost demand model as an environmental policy assessment tool: a review of literature. *Western Journal of Agricultural Economics* 11:164-178.
- Witter, Daniel J., William W. Shaw, David A. King, and Merton T. Richards. 1978. Nonconsumptive wildlife enthusiast visiting southern Arizona: Their beliefs about wildlife management programs and policies. Paper presented at the Arizona-New Mexico Wildlife Society-American Fisheries Society Annual Conference, Feb. 3-4, 1978, Douglas, AZ.
- Zube, Ervin H., James L. Sell, and Jonathan G. Taylor. 1982. Landscape perception: Research, application and theory. *Landscape Planning* 9:1-33.

Uncertainty and Risk in Forest Management¹

Aregai Tecle, Lucien Duckstein, W. Wallace Covington, and D. Brent Wood²

Abstract.--A framework is developed for risk and uncertainty analysis in forest management. The elements of this analysis are driven by five main issues, the first of which is forest regeneration. The first framework element is the set of hazards such as fuel and weather conditions that create a fire hazard; the second element is the set of hazardous events triggered by some random element, such as a forest fire ignited by lightning. The third element is the set of actions or decisions, and the fourth one consists of criterion functions, such as loss of wildlife habitat as a result of fire. A probabilistic model which is applicable to any risky situation is developed, in which the uncertain parameter is taken as a function of the hazard descriptors.

INTRODUCTION

The purpose of this paper is to provide a framework for risk analysis in forest management. This framework is analytical and includes uncertainties due to, for example, weather and climatic forecasting. The methodology is illustrated by means of an analysis of forest fires, as well as other hazardous events, and is developed for application to decision support systems such as the Terrestrial Ecosystem Analysis and Modeling System (TEAMS) of Covington and others (1988) which has been used for both educational and forest management purposes (Wood and others 1989).

Risk analysis is a procedure of determining the probability of occurrence of a particular undesirable state of nature. The occurrence of a particular event may be uncertain if we do not have

any knowledge about its probability occurrence. A complete risk analysis under uncertainty may be performed according to the following steps (Duckstein and others 1989):

1. Identification of the hazard, H , for example, large quantities of fuel coupled with hot, dry weather and electric storms (lightning).
2. Estimation of the probability, $P(H|\theta)$, of the hazard, H , where θ is a parameter vector depending on the hazard triggering factors such as lightning or throwing a burning match stick or a burning cigarette butte in a forest environment.
3. Definition of the hazardous event, x , and estimation of the conditional probability, $P(x|H, \theta)$, of the occurrence of the event.
4. Determination of the consequences, L , of the hazardous event, for example a loss of habitat of a given wildlife species, siltation of downstream reservoir.
5. Evaluation of the effects of remedial, control or management activities A_j on the consequences (L), such as the effect of timber harvesting on wildlife losses, or the effect of forest tree regeneration on sediment loss. The function L may be single dimensional (e.g., economic), or

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²Aregai Tecle is Assistant Professor, W. Wallace Covington, and D. Brent Wood are Professors, School of Forestry, Northern Arizona University, Flagstaff, and Lucien Duckstein is professor, Systems and Industrial Engineering Department, University of Arizona, Tucson, Arizona.

multi-dimensional in nature. This step thus involves two tasks:

- 5a. definition of the set of available actions or decisions $\{A\} = \{A_1, \dots, A_j\}$.
- 5b. definitions of a set of objective, criterion or loss functions $L(x,A)$.
6. The output of such a risk analysis is a set of probability distributions and criterion values including risks.
7. The output may be presented in a decision support system, which includes two or three-dimensional maps of the area under consideration.

These seven analysis steps are related as sketched in Figure 1. In the next section, the issues pertaining to the consequences of hazardous events on forest management are first listed (Step 4 above and in Fig. 1), to focus the paper on relevant elements.

ISSUES

By issues we mean the physical consequences of hazardous events such as fires, floods, or droughts on the forest system. Five issues are considered in this paper.

- I1. Forest regeneration after a destructive event, such as clear cut harvest, or fire, measured as the number of saplings per unit area per time period (in years) after the event.
- I2. Threat to an endangered species measured as a decrease in the population of a particular species that serves as an index of habitat capability.
- I3. Deterioration of wildlife habitat measured as percent destruction of the habitat.
- I4. Aesthetics degradation measured as change in scenic beauty estimator.
- I5. Water yield measured both in volumetric and economic units, and water quality, measured by indices of concentration of pollutants.

These five issues are related both physically and statistically. In particular, the first one, (I1) forest regeneration, is strongly related to the

four other issues. Next, a set of hazardous events, corresponding to Step 3 in figure 1, is described.

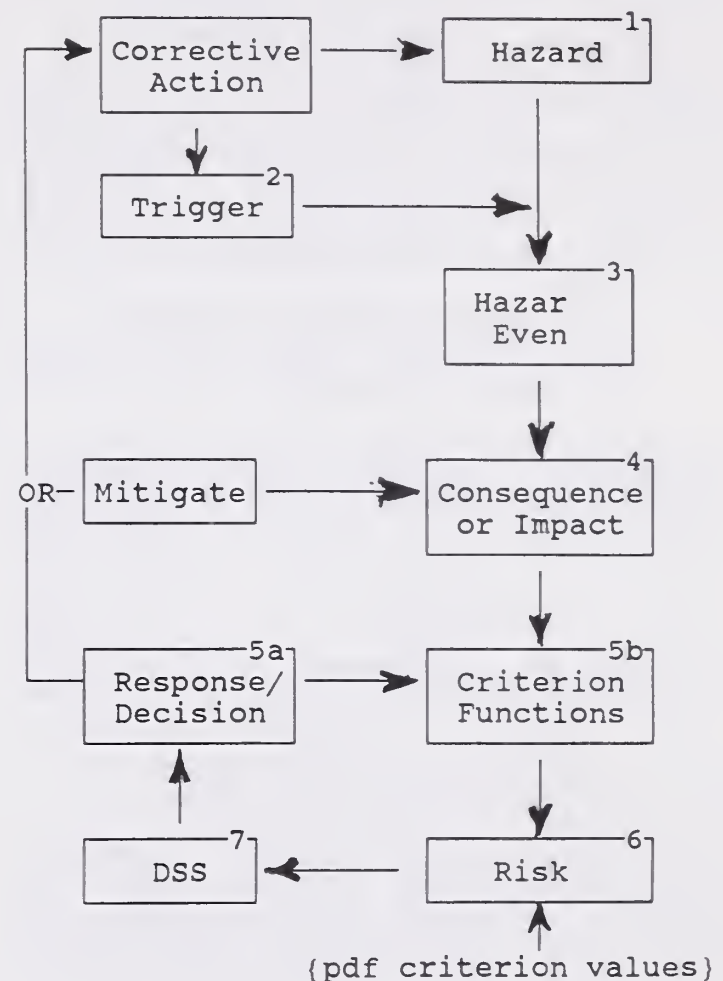


Figure 1. Diagrammatic Representation of Risk Analysis Procedure

HAZARDOUS EVENTS

Here, five broad categories of hazardous events are listed. Again, there may be physical and statistical dependence among several of these events.

- E1. Fires, either wildfire or controlled burning, are influenced by unexpected disturbances. These disturbances may be due to natural processes such as volcanic eruption, and lightning, or anthropogenic in origin such as camping and other recreational use.
- E2. Extreme weather or climatological phenomena, such as intense precipitation or prolonged droughts.
- E3. Erosion which may be caused by either natural or man-made hazards.

- E4. Atmospheric pollution, such as sulfur from smelters or power plants, and acid rain.
- E5. Human caused stress stemming, for example, from grazing, harvesting activities, pollution loading, or exceeding the capacity of a recreational area.

Two conditions are necessary for a hazardous event to occur:

- (a) A hazard must be present (e.g. fuel)
- (b) A triggering mechanism must be activated (e.g. ignition of fuel through lightning).

These two conditions, corresponding to steps 1 and 2, respectively, in figure 1, are described in the following sections.

HAZARDS

A hazard is a situation which may lead to or cause an unfavorable events to occur. For example, a loaded gun pointed at a person is a hazard. And if the trigger is pulled, the hazard results in injury or death, which a hazardous event. The event is determined by the presence of both the hazard and the trigger. This implies that the presence of a hazardous environment does not necessarily entail a hazardous event. The occurrence of the latter can be prevented either by correcting the hazard, or by avoiding any mechanisms that may trigger the occurrence of a hazardous event.

Hazards, H, in forest management which relate to the issues described in above include the following:

- H1. Fire hazard which increases amount and areal distribution of fuel accumulation, dry and hot weather conditions, combined with a high probability of occurrence of an ignition triggering mechanism such as lightning or human-induced fires.
- H2. Timber harvesting combined with steep slope conditions and easily erodible soil characteristics is a hazard which may enhance soil erosion, flooding, loss of wildlife habitat, etc.
- H3. Extreme rainfall or drought conditions may have devastating effects on the fauna and flora in a forest system. Both extreme rainfall and drought conditions are considered to be hazards because each has the capacity

to cause unfavorable events. Extreme rainfall, for example, may cause flooding, loss of crops, or young trees. Likewise, drought may cause loss of wildlife, or stunt or destroy the healthy growth of forest trees.

- H4. Grazing activities which cause overgrazing and soil detachment through tramping the ground by livestock may in turn make the ground amenable to erosion, and decrease the amount of the rainfall that can infiltrate into the soil.
- H5. Pollution hazard caused by an existence of emission source combined with necessary wind conditions; the triggering mechanism is the operation of the emission source and the event is the resulting level of air pollution.
- H6. Transportation policy - building of roads, allowing access to off-road vehicles, and frequency of vehicular use.

As previously pointed out, each of these hazards may cause a hazardous event, but not necessarily so. For example, grazing combined with intense precipitation may or may not cause erosion; also, a thunderstorm over forest fuel does not always result in a fire.

Actions that may be taken to prevent or mitigate the effects of hazardous events (Step 5a in Figure 1) as well as some possible criterion functions (Step 5B) are listed in the next section.

ACTIONS AND CRITERION FUNCTIONS

Actions include, but are not limited to the following alternatives:

- A1. Harvesting, including transportation of products.
- A2. Selective cutting and prescribed burning.
- A3. Artificial regeneration.
- A4. Grazing policy.
- A5. Recreation capacity setting policy.
- A6. Transportation policy.
- A7. Information dissemination.

Criterion functions include, as mentioned earlier, the following items:

- C1. Forest regeneration scale.
- C2. Habitat (area type and quality, alos food and shelter) of endangered species.

- C3. Wildlife conditions (number, diversity and health condition).
- C4. Aesthetic scale.
- C5. Water quantity, value of water for various water supply uses (hydrologic) and water quality indices.

STOCHASTIC METHODOLOGY

Consider only fire hazard H1. The first phase of the study is to determine the probability of the hazardous event. The probability of a hazardous fire event is sought directly, as

$$P(X=x|\theta(H)) \quad (1)$$

where $\theta(H)$ is the parameter of the probability density function (pdf) of x . Assume, for example, that the probability of fire at a given site follows a Bernoulli or point binomial pdf with mean θ . This relationship is represented by:

$$F_x(x|\theta) = x^\theta(1-x)^{1-\theta}, \quad (2)$$

where $x=0,1$ and $\theta \in [0,1]$

In this analysis, θ itself is a random variable, with a probability density function (pdf) $g(\theta)$ to be determined by combining various sources of information. Thus, a linear regression of θ in the elements of hazard (H) may be performed. For instance, let fire hazard (H) be a function of fuel (B), dryness (D), temperature (T), wind speed and direction (W), number of lightning strikes (N), then a regression equation expressing the relationships between these elements can be constructed in the following form:

$$\theta = a_1 + a_2B + a_3D + a_4T + a_5W + a_6N + \epsilon \quad (3)$$

Remember that θ is the mean probability of fire occurrence if the conditions described by the values of the independent variables are present. The actual occurrence is represented by a non-controllable random variable x which can take on values of either 0 (no fire) or 1 (fire).

If equation (3) is used, then θ has the pdf of ϵ , which is taken as a normal distribution, $N(0, \sigma, \epsilon)$ with a mean of 0 and standard deviation σ . This pdf should be truncated since θ is an element ranging in value between 0 and 1, $\{\theta \in [0,1]\}$. Other sources of information can be combined with the model in equation (3) in particular:

- regional information stemming from the same type of forest at different sites
- model based information (simulation)
- subjective information assessed from experts
- observation data

Bayes Theorem is used to pool all sources of information together. For example, a subjective pdf $g(\theta)$ is combined with the information $N(\theta|\text{REG})$ given by the regression by applying Bayes Theorem to obtain a so-called posterior pdf of θ .

$$g(\theta|\text{REG}) = Kg(\theta)N(\theta|\text{REG}) \quad (4)$$

where K is a normalizing constant.

Once a model such as the one in Equations 3 and 4 has been calibrated, a forecasting of the weather related variables D, T, W , and N , together with an estimation of fuel amount B , yields an estimate of fire hazard (θ) encoded as the mean of pdf in Equation (2). The probability of fire event can then be estimated from Equation (1).

MULTICRITERION ANALYSIS

Next, every criterion function C_i , $i=1, \dots, I$, here $I=5$, can be expressed as a function of action A_j , $j=1, \dots, J$, here $J=5$ and hazardous event x (Tecle et al. 1988) as follows:

$$C_i = C_i(A_j, X) \quad (5)$$

The expectation of C_i over X yields a function of θ , whose expectation must again be taken, thus

$$E^\theta E^x(C_i(A_j, X)) = E^\theta(C_i(A_j, \theta)) = R_i(A_j) \quad (6)$$

which is a so-called "risk cost."

The action or decision is sought, which minimizes $R_i(A_j)$. This formulation makes it possible to calculate the worth of perfect and of sample information (Davis and others 1972; Ang and Tang 1984).

SUMMARY AND CONCLUSIONS

A framework has been developed to study uncertainty and risk in forest management. In the example presented herein, the framework is driven by five issues, and includes six hazards, five hazardous events, five criterion functions, and seven possible actions. Only the uncertainty in the weather

variables has been considered; it is encoded for example as the random mean of the pdf of hazardous event occurrence X, which, here, has been taken as a Bernoulli variable for the sake of simplicity.

The framework which makes it possible to combine multiple sources of information leads to the use of multiple criteria (Tecle and others 1988) to evaluate the consequences of a hazardous event and determine the appropriate action for mitigating or controlling the effects of such an event.

REFERENCES CITED

- Ang, A.H.S., and W.H. Tang. 1984. Probability Concepts in Engineering Planning and Design, Vol. 2, John Wiley and Sons, New York, N.Y.
- Covington, W.W., D.B. Wood, D.L. Young, D.P. Dykstra, and L.D. Garrett. 1988. TEAMS: A Decision Support System for Multiresource Management. Journal of Forestry, 86(8):25-33.
- Davis, D.R., C.C. Kisiel, and L. Duckstein. 1972. Bayesian Decision Theory Applied to Design in Hydrology. Water Resources Research, 8(1):33-42.
- Duckstein, L., A. Bardossy, T. Berry, and I. Bogardi. 1989. Health Risk Assessment Under Uncertainty: A Fuzzy Risk Methodology. Proceedings (in press): Engineering Foundation Conference on Risk-Based Decision Making, Santa Barbara, CA Oct. 15-20.
- Tecle, A., M.M. Fogel, and L. Duckstein. 1987. Multicriterion Analysis of Forest Watershed Management Alternatives. Water Resources Bulletin, 24(6):1169-1178.
- Wood, D.B., B.E. Fox, and W.W. Covington. 1989. Computer-Based Approach for Teaching Multiresource Management: A Decision Support System to Aid Student Understanding. Journal of Forestry, 87(11):11-16.

Trends in Residential Development and Water Usage Below the Mogollon Rim of Central Arizona¹

Alvin L. Medina²

Abstract.--Trends in home development within the ponderosa pine type were examined for the region of central Arizona. Home development rates spiralled since the mid-1950's, with about 92% of all homes constructed since 1955. The potential for additional development in the region is greater than 2-fold, since about 47% of private lands remain unsubdivided and about 50% of subdivided lots remain undeveloped. Increased demand for domestic water has paralleled home development to the extent that development has declined due to the lack of water. In the community of Pine, for example, consumption rates exceed the amount provided by stream base flows.

INTRODUCTION

Second-home development in rural areas of the Southwest has increased greatly in recent years. In Arizona, several economic and social factors, including rapid population growth, prosperity, and increased land value, have influenced second-home development in the Mogollon Rim region (Bond and Dunikoski 1977, Lindquest 1972). Homes and land subdivisions along riparian zones and in high-elevation ponderosa pine forests are in greatest demand because the stream and forested environments are esthetically pleasing and water is available. As a result, water consumption by home subdivisions has increased proportionately with development, resulting in limited water supply for some communities and changes in perennial streams. These changes in streamflow potentially threaten riparian vegetation and fishery resources, although these threats are difficult to assess directly or indirectly (Bormann et al. 1970).

Various researchers have examined water related problems (i.e., quality, socioeconomic) associated with second-home development (Brickler and Utter 1975, Lewis 1980, Morgan 1978, Ponce

and Dederick 1979, Segall 1975). However, most studies were primarily concerned with assessing the impacts on water quality. Still other studies (Johnson and Carothers 1982) have focused on recreational problems affecting riparian habitats. Information on the trends in home development and water consumption for forested areas in the Southwest is scant, and limited mainly to unpublished reports (Bond and Dunikoski 1977). Therefore, this study specifically (1) examined the trends in regional residential development within the ponderosa pine type of central Arizona, and (2) relates water usage by a typical community of Pine, Arizona to potential regional development.

STUDY AREA

The study area is near the geographic center of Arizona in northern Gila County, immediately below the Mogollon Rim escarpment and on the Payson Ranger District, Tonto National Forest (Fig. 1). Steep, mountainous canyons emanating from the escarpment dissect the landscape from east to west. Vegetation consists of Petran Montane Conifer Forest (Brown and Lowe 1980). The ponderosa pine type is interspersed with the Great Basin Conifer Woodland type.

Nearly 65% of total precipitation occurs in winter, primarily as snow. Summer precipitation is by localized monsoon showers. Mean annual precipitation is 635 mm and ranges from 550 to 760. Mean annual temperature is 14°C and ranges from -10°C to 32°C. Base flows of 42.5 l/sec are common in most creeks, with peak flows greater than 170 m³/s (USDA Forest Service 1966). The origin of most streams is groundwater flow, which emanates from the Coconino sandstone-shale contacts found on the south face of the Mogollon Rim escarpment at elevations of about 2180 m.

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²Research Range Scientist, USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Forestry Sciences Laboratory, Arizona State University Campus, Tempe, Ariz. 85287-1304 (U.S.A.).

³Peterson, Mike. 1989. Personal communication. Gila Co. Dev. Div., Globe, Arizona.



Figure 1.--Location of study area below the Mogollon Rim on the Payson Ranger District, Tonto National Forest.

The region is a popular vacation, retirement, and recreation center. Summer residents exceed permanent residents 2- to 3-fold. Commercial sectors are heavily dependent on tourism, summer residents, and recreationists (Arizona Department of Commerce 1986). Settlement of the area, which started near 1890, consisted mainly of cattle ranchers until recently.

Residents of Pine, Arizona use stream water from Pine Creek for irrigation and domestic

purposes. A detention dam constructed in 1965 in Pine Creek above the community diverts upstream water, which is piped to the residential area below. Between May and October, most of the piped flow is used for irrigation by residents having water rights. This diversion causes ephemeral flow in the stream reaches below the detention dam during the summer. In contrast, base flow above the diversion during the summer is maintained at approximately 45 l/s (USDA Forest Service 1966).

METHODS

Trends in home development since 1885 for the region were determined by examining Gila County plat records (Redi-Data 1987) and recording the number of homes constructed. Records were examined for areas only within the ponderosa pine type indicated on figure 1, all of which are within the Payson RD. Only private homes were used for this analysis. Construction trends were graphed to show differences among years. Residence was determined from local addresses listed in the county records. Numbers of vacant lots available for development were also noted. Of the roughly 4,000 ha of private land within the study area, about half are subdivided for home development. Records from the local water company (E & R Water Company, Inc., Mesa, Arizona) were used to estimate water consumption for the community of Pine.

RESULTS

Regional housing development trends are shown in figure 2. Only about 8.1% (362 homes) of all homes built by the end of 1987 were constructed prior to 1956. The percentage of the total doubled (17.8%) between 1956 and 1960 and nearly doubled (33.4%) again between 1961 and 1970. The largest percent increase in housing development occurred from 1971 through 1985, with a 16.2% increase between 1966-1970 and 1971-1975, 24.7% increase between 1971-1975 and 1976-1980, and 23.6% increase from 1976-1980 to 1981-1985. Approximately 92% of all homes were constructed since 1955. Although 4,454 number of homes were built between 1885 and the end of 1987 within the ponderosa pine type, about 47% of private parcels still remained undivided. Thus, the potential for additional home development in the region is greater than 2-fold.

Nearly 62% of the residences were owned by nonresidents, i.e., people outside the local mailing area, with most being from the Phoenix or Tucson metro areas (fig. 3). Nonresidents make general use of their temporary residences primarily during the summer months (May through August) and weekends. Most homes are constructed in streamside environments (fig. 4) and on adjacent slopes and ridges.

Average monthly water consumption rates per household in the community of Pine were roughly 10,730 liters for the period 1975-1985, based on an average of 1,602 households. Winter and summer consumption rates were about 8,500 liters and 12,950 liters, respectively. The largest use (mean=45.1%) occurred during the summer from June through August (fig. 5), which coincides with the period of low flow in Pine Creek and the influx of summer residents.

DISCUSSION

Home development in the region increased dramatically after World War II. One plausible

explanation for this rapid growth may have been increased affluency of nonresident owners from the metro areas of Phoenix and Tucson, who own nearly three-fourths of the residences. Reasons for owning a residence in the forested environment are probably a desire to escape from the valley heat during the summer and weekends and recreate in the general area, investment in real estate, and preretirement plans. Records show most lots could be purchased for about \$4,000 to \$6,000 in the 1950's (Redi-Data 1987). Current prices for similar lots range from \$25,000 to \$30,000, and up to \$60,000 for improved lots. Figure 3 indicates a general increase in home ownership by residents, who are likely retirees. The sharp decline in construction after 1985 was probably due to a variety of reasons, including adoption of more stringent building codes by Gila County, reduced federal income tax opportunities for second homes, and a building moratorium imposed in the Pine community because of water shortages.

The growth rate observed during the last 15 years, especially along streamside environments, undoubtedly increased the demand for water from streams that are only capable of supplying a limited amount of water. Early accounts of water usage for the area report an ample supply of "good" water from creeks, springs, and streams during early 1900's, but by 1930 drilled wells were needed to supplement surface waters (Northern Gila County Historical Society 1984). Bond and Dunikoski (1977) also reported considerable variation in average water usage patterns throughout the region. They estimated an average annual use of 74,409 l/household and a summer usage rate of 11,570 l/household/month for a residential area in Pine. This estimate is lower than the 12,950 l/household/summer-month reported here.

Using the reported average number of 1,602 households and a summer use rate of 12,950 l/household/month for the Pine area, water usage is about 20.7×10^6 l/summer-month or roughly $20,746 \text{ m}^3$. The flow of 135 l/s from the detention dam provides about $5,832 \text{ m}^3$, or about one-fourth, of the estimated summer demand. The deficit is made up from ground-water wells. These calculations show the community may be using more water than base flows in the stream provided during the summer months. During the summer of 1989, the water shortage became severe enough that domestic water was trucked in to the community. In addition, about 45% of all home tracts sold remain vacant, hence the potential demand for domestic water could double or reach about $41,500 \text{ m}^3$. Additional water is also needed by commercial enterprises, fire suppression and other unspecified uses.

There are other potentially negative impacts that could be associated with residential development in forested environments. Some of these include a general loss of habitat for wildlife as a result of site development, roads, and increased human disturbance. In some cases,

TREND IN RESIDENTIAL DEVELOPMENT

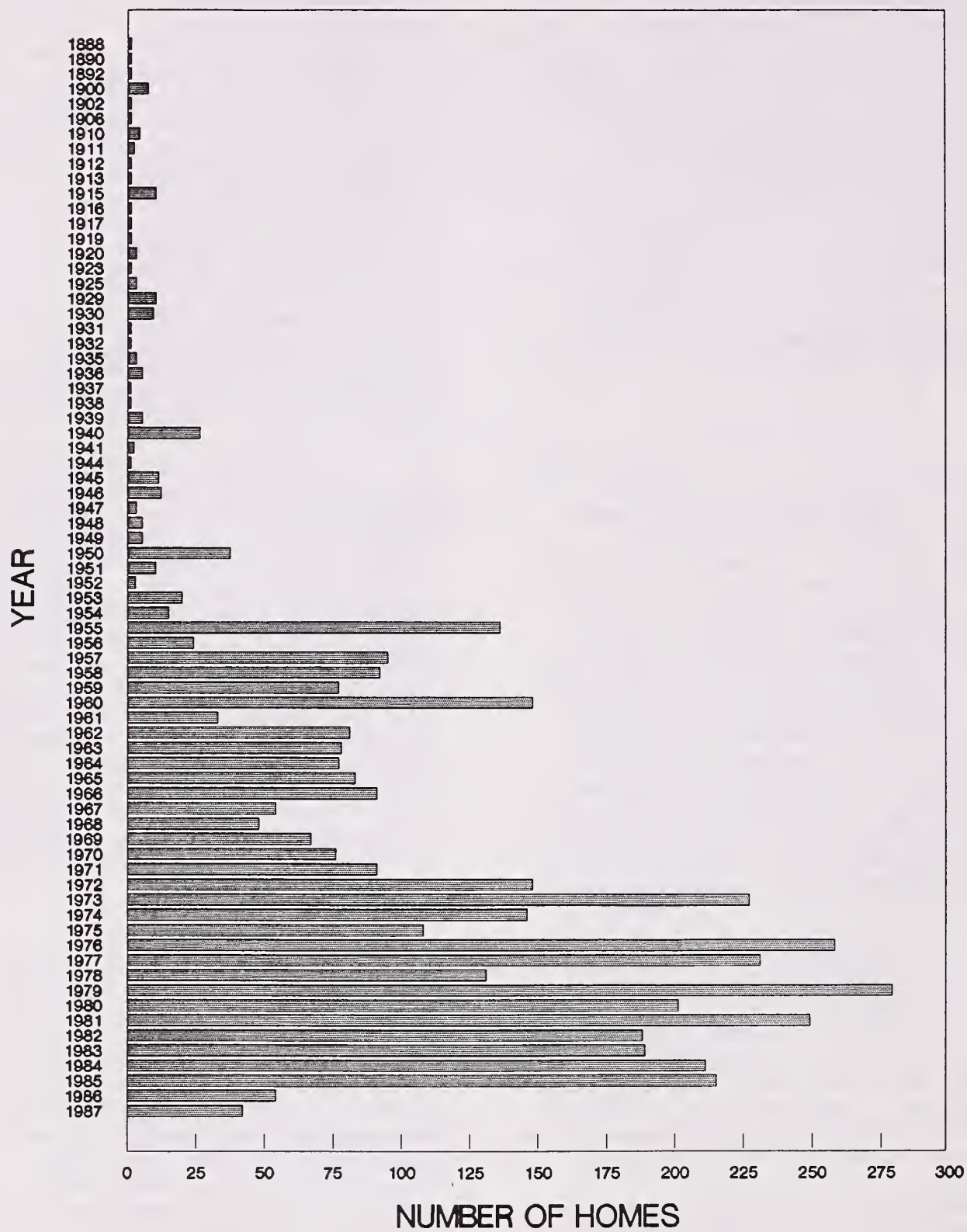


Figure 2.--Trends in residential development within the ponderosa pine type, central Arizona.

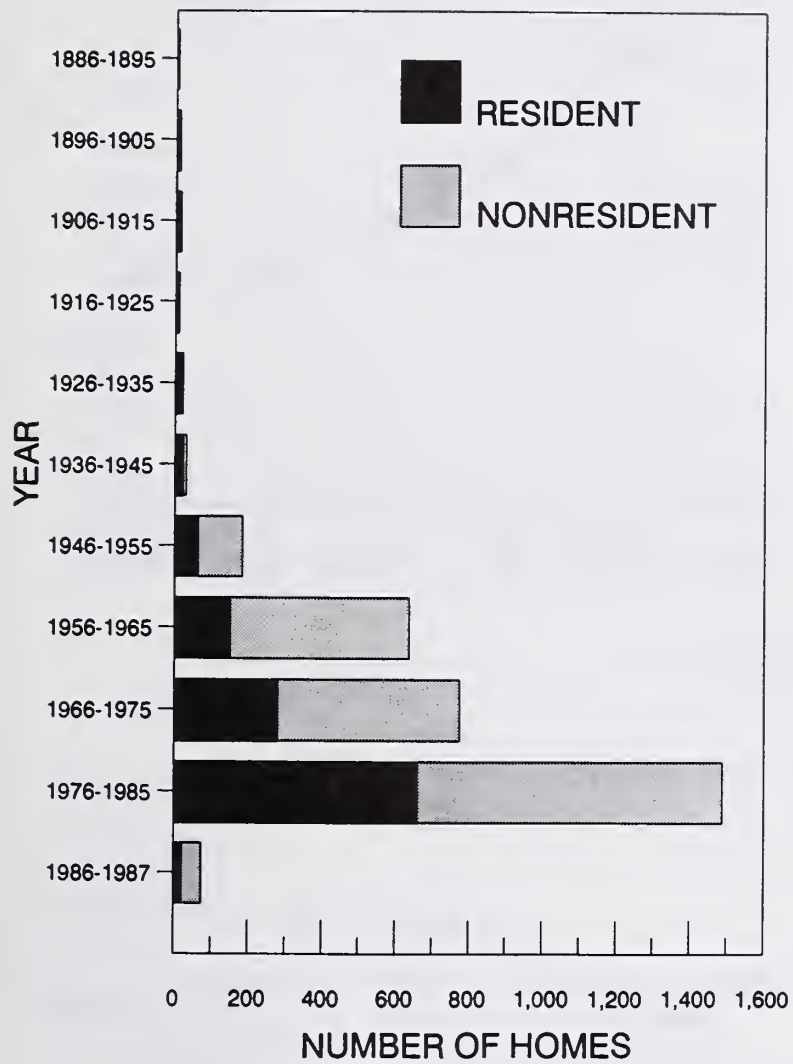


Figure 3.--Trend in home ownership by residents and nonresidents.

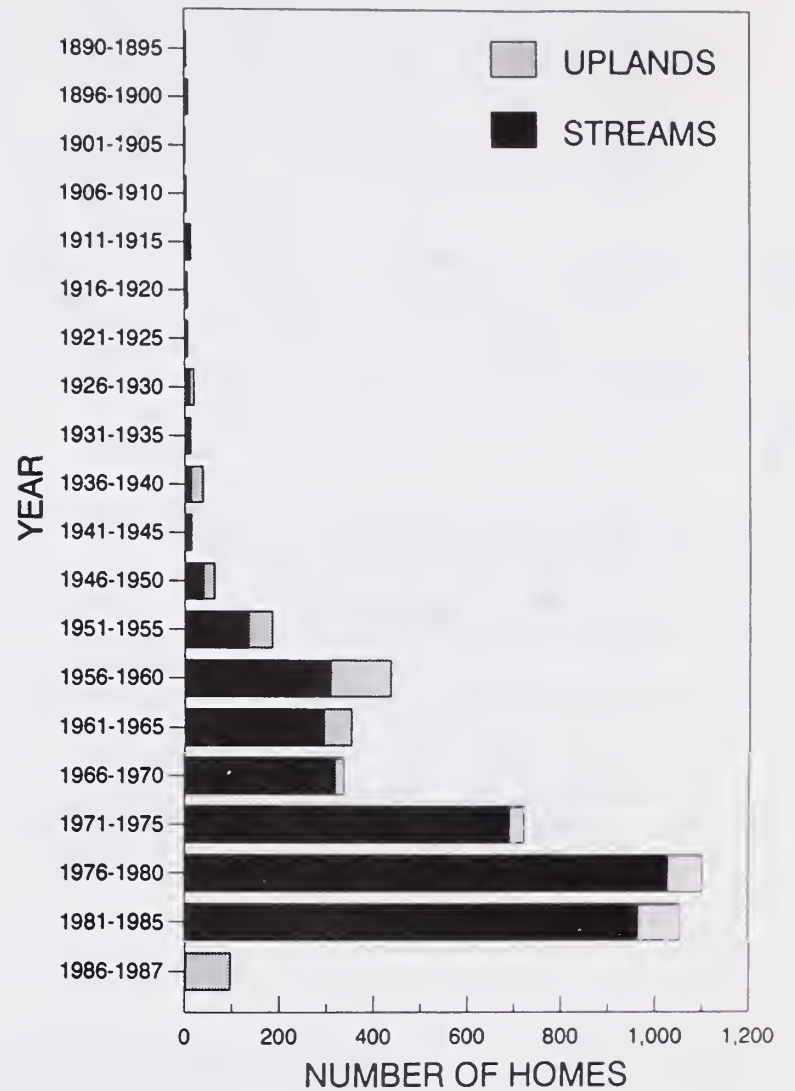


Figure 4.--Trend in residential development along streams and uplands within the ponderosa pine type, central Arizona.

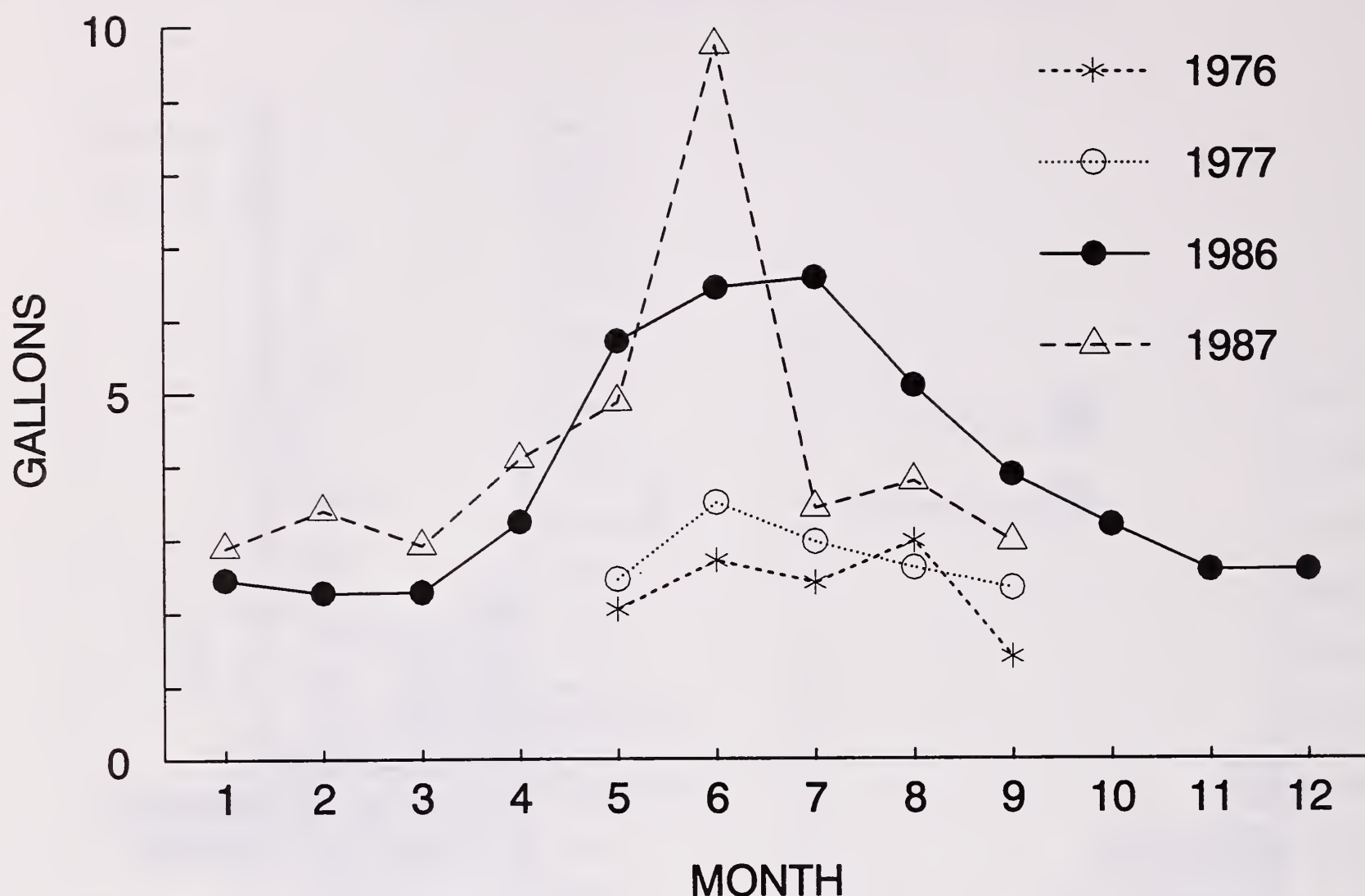


Figure 5.—Trend in water usage for the community of Pine.

stream and ground water quality may deteriorate because of vegetation and soil disturbance (Grant and Lewis 1976), which may result in increased surface runoff (Trotta 1979).

CONCLUSIONS

Home development rates have spiralled since the mid-1950's in the Pine area and the region below the Mogollon Rim. Increased demand for domestic water has paralleled home development to such an extent that development has declined due to the unavailability of water. In the community of Pine, for instance, consumption rates exceeded the amount provided by stream base flows. Water demands are greater during the summer because summer residency increases 2 to 3 times, but a greater potential exists for future water shortages because about 47% of private lands remain unsubdivided and about 50% of subdivided lots remain undeveloped.

LITERATURE CITED

- Arizona Department of Commerce. 1986. Pine/Strawberry community profile. Arizona Department of Economic Security. 2 p.
- Bond, M.E.; Dunikoski, R.H. 1977. Impact of second-home development on water availability in north central Arizona. Tempe: Arizona State University, Bureau of Business and Economic Research. 88 p.
- Bormann, F.H.; Siccama, T.G.; Likens, G.E.; Whittaker, R.H. 1970. The Hubbard Brook ecosystem study: composition and dynamics of the tree stratum. *Ecological Monographs*. 40: 373-388.
- Brickler, S.K.; Utter, J.G. 1975. Impact of recreation use and development on water quality in Arizona: an overview. In: Eisenhower Consortium Bull. 1. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 195-201.

- Brown, D.E.; Lowe, C.H. 1980. Biotic communities of the Southwest. Gen. Tech. Rep. RM-78 map. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.
- Grant, M.C.; Lewis, W.M. Jr. 1976. Nutrient movement in a mountain watershed supporting light residential development. Final Rep. Eisenhower Consort. Proj. 16-529-CA. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.
- Johnson, R.R.; Carothers, S.W. 1982. Riparian habitats and recreation: interrelationships and impacts in the Southwest and Rocky Mountain region. Eisenhower Consortium Bull. 12. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 31 p.
- Lewis, G.D. Compiler. 1980. The Eisenhower Consortium for western environmental research: research highlights, 1972-1980. Eisenhower Consortium Bull. 8. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 31 p.
- Lindquest, L.A. Compiler. 1972. Mogollon Rim area--land use planning study. Phoenix, AZ: USDA Forest Service, Tonto National Forest.
- Morgan, J.N. 1978. Economic and ecological impact of second home developments on local areas. Eisenhower Consortium Final Rep. 16-597-GR. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 60 p.
- Northern Gila County Historical Society. 1984. Rim country history. Payson, AZ: Rim Country Printery. 194 p.
- Ponce, S.L.; Dederick, J. 1979. Impact of second home developments on water quality in areas of low precipitation. Eisenhower Consortium Final Rep. 188 (unpublished). Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 94 p.
- Redi-Data, Inc. 1987. Gila County, Arizona. Miami, FL: Real Estate Data Inc. Microfiche 1987: E01-E09.
- Segall, B.A. 1975. The effects of second home and related vacation development use on water quality in Arizona. In: Eisenhower Consortium Bull. 1: Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 221-226.
- Trotta, P.D. 1979. Impact of development on stream flows. Final Rep. Eisenhower Consort. Proj. 16-792-GR. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 50 p.
- USDA Forest Service. 1966. Hydrologic analysis and report for the Pine Canyon watershed, Payson Ranger District, Tonto National Forest. Unpublished report. Phoenix, AZ: USDA Forest Service, Tonto National Forest. 34 p.

Multiresource Management, Decision Support Systems, and Expert Systems: Moderators' Comments

Dennis P. Dykstra and Ronald L. Trosper
NAU School of Forestry

Multiresource forest management is by definition an interdisciplinary activity. Few forest managers, in this age of specialization, have the expertise to fully evaluate the enormous range of potential multiresource impacts associated with forestry activities such as timber harvests, range improvements, or recreation developments. The difficulty of making such evaluations, in fact, was one of the central arguments that was made in earlier times in favor of developing single-resource forest management plans rather than a single, comprehensive multiresource forest management plan.

The development that represents perhaps the greatest single advancement in bringing the practice of multiresource forest management closer to reality is the computer, and especially the personal computer. For the first time in history, scientists involved in multiresource forest management research can be assured that personnel involved with the everyday practice of forestry have available to them powerful computing capabilities that permit immediate access to enormous databases, virtually instant calculations, and the rapid preparation of graphical results that can improve both communication and decision making, and can also reduce the chances of interpretation errors.

Much of the research that is currently underway relating to the practice of multiresource forest management involves the use of computer tech-

nology by interdisciplinary teams, simply because of the sheer difficulty of comprehending all of the interrelationships inherent in forest ecosystems. The six papers in this session explore several aspects of computing technology as related to the practice of multiresource forest management. The first three papers consider the Terrestrial Ecosystem Analysis and Modeling System (TEAMS), a multiresource forest management decision support system developed by the School of Forestry at Northern Arizona University. The paper by Covington and his colleagues explains the foundations of the TEAMS model; the papers by Wood and others and by Fox and others then report on experience using the model as a tool to improve project-level planning by the Navajo Forestry Department and by the USDA Forest Service.

The remaining three papers in this session consider several independent but interrelated subjects that are important to multiresource forest management. The paper by Tecle and his colleagues discusses methodologies for resolving conflicts in forest planning through the use of multiobjective decision analysis. Long and Wagner then report on an effort to develop a microcomputer-based expert system for insect pest management decision making. Finally, Patton and Severson discuss the use of a relational database coupled with artificial intelligence software to improve retrieval of information related to wildlife habitat relationships.

Current Status of the TEAMS Decision Support System: Structure, Development, and Application¹

W. Wallace Covington, D. Brent Wood, Aregai Tecle, and Bruce E. Fox²

Abstract: TEAMS (Terrestrial Ecosystem Analysis and Modeling System) is a computer based decision support system designed to aid in developing site specific treatment alternatives. TEAMS combines a geographical information system, a multiresource simulation model, an optimization module, and a graphics output display package, all organized around a relational database management system. TEAMS has been used to develop treatment plans for timber sales and multiproject, watershed level management units. These applications, as well as use in teaching, have led to identification of potentially useful design and operational improvements in decision support technology. These enhancements are in the areas of remote sensing technology, geographical information systems, simulation models, automated goal seeking, and conflict resolution procedures.

INTRODUCTION

A central problem confronting public forestry today is how to efficiently implement forest level land management plans while fully addressing both short and long term environmental consequences of a full range of management alternatives. Furthermore, because treatment location must be considered with respect to other ecosystem patches, surface water sources, topographic position, and road and trail systems, spatial pattern of treatments is also crucial. Thus both temporal and spatial changes must be included in the analysis.

Despite the longstanding recognition of the necessity for taking a systems approach for accomplishing this task, there has been an alarming lack of practical procedures and technologies for implementing integrated multiresource management on the ground.

For national forests, forest plan implementation means selecting, scheduling, and administering management practices that meet forest plan direction as well as the requirements of both the National Forest Management Act (NFMA) of 1976 and the National Environmental Protection Act (NEPA) of 1969. Thus forest plan implementation (USDA Forest Service 1987) involves:

1. identifying feasible management practices;
2. analyzing and evaluating the short and long range consequences of feasible actions;
3. deciding upon an appropriate course of action;
4. developing budgets;
5. executing and administering projects; and
6. monitoring and evaluating the results of the activities.

¹Paper presented at the Multiresource Management of Ponderosa Pine Symposium. Flagstaff, AZ. November 14-16, 1989.

²W.W. Covington and D.B. Wood are professors, A. Tecle and B.E. Fox are assistant professors, School of Forestry, Northern Arizona University, Flagstaff, AZ

A conceptual framework for integrated analysis is available in several publications which detail a stepwise procedure for analysis and documentation in support of land management plan implementation (e.g., Jameson and others 1982, USDA Forest Service 1988). However, interdisciplinary teams trying to follow such procedures have found it all but impossible to fully address the temporal and spatial consequences of a broad range of management scenarios. There has been a widespread hope that the acquisition of geographical information systems (GIS) technology will go a long way toward alleviating this problem. However, GIS is far from a panacea. Although its utility in map based information management, analysis, and display is unquestionable, GIS alone deals only with current conditions.

A mechanism for is needed for generating a full range of treatment possibilities, forecasting their temporal and spatial consequences, narrowing the treatment possibilities down to those which meet overall management criteria, and finally choosing the best of these possibilities. Such an analysis done manually would require an inordinate amount of time. Computer automation can accomplish many of the tedious steps in such an analysis and, if used in conjunction with a systematic, stepwise interdisciplinary team process, it can greatly facilitate forest plan implementation.

This paper is presents an overview of the complex nature of implementing multiresource management, to describe a computer aided approach for assisting interdisciplinary teams in using the vast array of information needed to accomplish the task, and finally to suggest some further development needs with respect to decision support for integrated resource management. The examples and terminology we will use will be most familiar to those involved in national forest management issues, but we believe that the concepts are generally applicable to other public natural resource management situations.

COMPLEXITY OF IMPLEMENTATION

Implementing multiresource management is a complex, information intense task. To begin with, the interdisciplinary team must know the current condition of the management area being considered. For example, if the area being considered has current or potential use for timber harvesting, wildlife habitat, downstream

water use, recreation, and livestock grazing, then the interdisciplinary team must have information on such resource condition indicators as density, vigor, and species composition of both trees and understory vegetation, watershed condition, water availability, transportation system condition, current wildlife habitat use, current recreation use, and so forth. Furthermore, this information must be referenced to specific locations within the management unit so that questions regarding landscape interactions, resource access, and so forth, can be addressed.

Next, the interdisciplinary team must assess treatment suitability for each ecosystem patch (which are perhaps 30-100 acres), including of course a no treatment option. In the case of timber harvesting, the management unit would be a stand. Then, for each feasible management scenario, the team must forecast both short and long term consequences for the various resource condition indicators for each management unit, as well as for the management area as a whole.

After having generated all of this information, the next step involves narrowing the choices down to some subset which meets the standards and guidelines specified by a land use plan and achieves the goals and objectives for the specific management area. The next task is to prepare documentation detailing the procedure and logic used to develop a full range of management scenarios and the tradeoffs among them; this documentation is then used by a manager to make a decision as to how to manage the area in question and to meet NFMA and NEPA requirements. Finally, treatments are implemented, monitored, and evaluated to compare what actually happened with what was anticipated.

Throughout this process it is incumbent upon the interdisciplinary team members to use the best available knowledge and procedures and to keep a detailed record of what occurs at each step in the analysis.

What actually happens today is a far cry from this. Some reasons for this are obvious. Typically, time is limiting and so are the number of individuals who can devote their full attention to the task in a team setting; scheduling meetings which most of the team members can attend often seems to be a insurmountable problem.

A more fundamental problem is how to cope with the tremendous amount of information needed in the analytical process. Furthermore, the complexity of the analytical task is such that tracking and understanding the logic behind the results and recommendations is practically impossible.

Automation of some of the more tedious parts of this procedure provides a mechanism for making the problem more tractable. Several types of software are available which can be used to solve parts of the overall problem. Geographical information systems facilitate spatial analysis, simulation models forecast growth and yield of trees and other resource conditions for various alternatives, heuristic software aids in developing decision rules for treatments to be considered, mathematical programming models facilitate automated goal seeking, database management systems allow rapid retrieval of information, and graphics output software can create displays which summarize the data so that it can be readily understood. However, analytical efficiency can be greatly improved by linking appropriate software modules to form an integrated decision support system. One such system, operational for southwestern ponderosa pine, is the TEAMS decision support system (Covington and others 1987, 1988).

STRUCTURE OF TEAMS

TEAMS is a general integrated decision support system framework for facilitating the analysis and interpretation necessary for comprehensive forest plan implementation. Currently TEAMS is designed for analysis of management areas ranging in size from a few thousand to tens of thousands of acres. It is intended to assist those concerned with project design and implementation in dealing with the complexity of multiresource ecological, economic, and political information in a integrated, iterative fashion.

Current versions of TEAMS (fig. 1) include a geographical information system, a multiresource forest activity simulation model, a mathematical programming model, a database management system, graphics output software, and the software which links them all together. Although the TEAMS concept could be used to integrate a wide variety of software, only the following module are currently being used:

1. Geographic information system -- ESRI's ARC/INFO and TYDAC Technologies' SPANS
2. Forest activity simulation model -- ECOSIM (Rogers et al. 1984)
3. Database management system -- Microrim's R:BASE
4. Graphics output software -- Microsoft's CHART

TEAMS projects outcomes of treatment alternatives and displays results in graphic, tabular, and map forms. With these results, managers may develop and test other treatment alternatives in response to perceived problems and opportunities. Thus TEAMS is an interactive tool that ultimately relies upon human judgement and expertise throughout the management process. Its function is to provide interdisciplinary teams with rapid feedback on the likely consequences of management alternatives being considered.

When using TEAMS, the primary unit of analysis is the stand, which is defined as a contiguous area which is relatively homogenous in terms of site quality and tree structure, age class, and density. Currently, stand-level alternatives consist of various harvesting and thinning options. The model also processes alternatives at the management unit level (as opposed to the stand level), including recreational developments and range improvement options.

Several versions of TEAMS have been developed. One version, for example, is designed to assist in the development of a 10-year annual treatment schedule and projects annual outputs for years 1 through 20. Another is designed for a 30-year treatment schedule by decade and projects outputs in 5-year increments through year 50. Each version has been customized to meet the concerns and needs for the particular problem being addressed.

TEAMS may be used in three ways. First, managers may directly specify how each stand within the management area should be treated. The system will then project and display on a computer screen, or in printed or plotted format, the predicted results of the prescribed treatment schedule that the managers can subsequently compare to goals, standards, and guidelines. Alternatively, managers may specify goals, standards, and guidelines for the unit, and TEAMS will

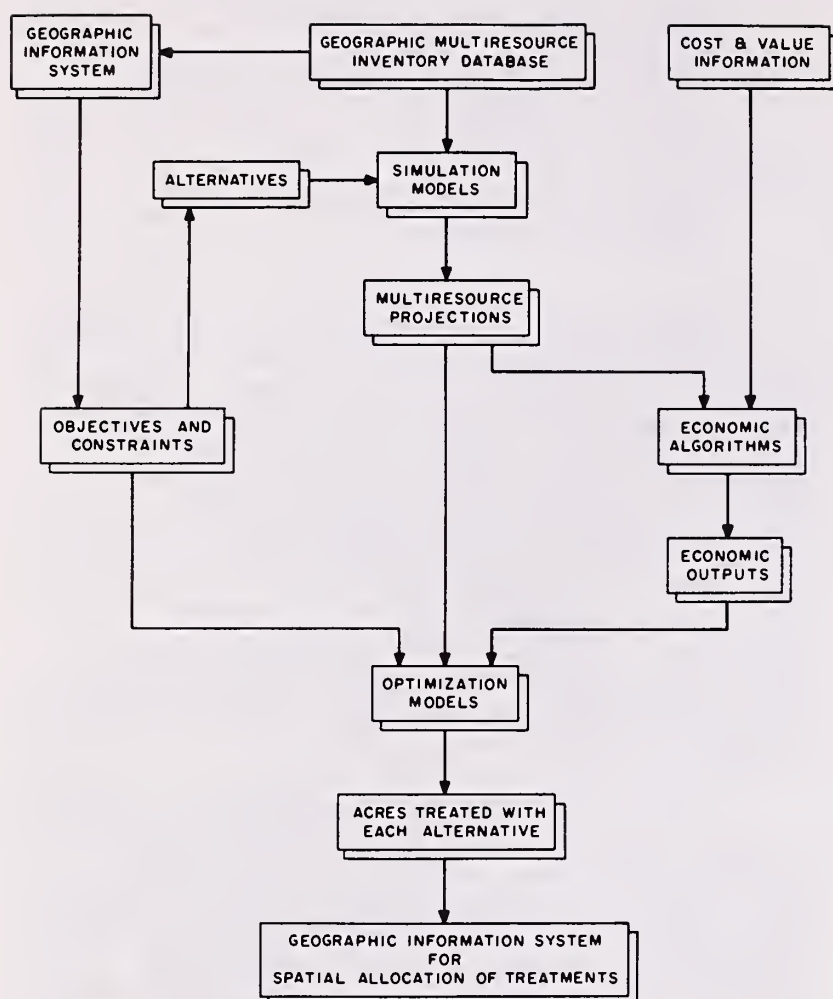


Figure 1. Flowchart for TEAMS decision support system

produce an optimal treatment schedule and project results. Finally, a combination of the first two approaches may be employed with prescriptions for some stands specified by the managers and others determined by the system. Regardless of the option chosen, management teams can use an evolutionary approach by making a series of computer runs, examining the output, and revising run conditions until they are satisfied with the overall design of the management regime. More detail regarding the structure of TEAMS is available in Covington and others (1988) and Covington and Wood (1989).

USE OF TEAMS

TEAMS has been used in support of forest management implementation analyses for multiresource management of ponderosa pine in Arizona, including timber sale analysis (Fox and others 1989) and

multiproject and watershed level analyses on the Coconino National Forest (Covington and Wood 1988) and Navajo Nation forest lands (Wood and others, this volume). It has also been used to facilitate teaching multiresource management concepts and procedures at both the graduate and undergraduate levels (Wood and others 1989). These uses have helped to identify opportunities for improving TEAMS to better suit the needs of those concerned with multiresource management.

ENHANCEMENTS IN DECISION SUPPORT

Our use of TEAMS on operational projects, as well as in research, development, and teaching applications, has helped us characterize some desirable features of decision support tools (Fox and others, in press). We will discuss needed improvements under the subheadings of: resource inventory and monitoring; geographical information systems; multiresource simulation models; automated goal seeking models; and conflict resolution procedures.

Resource Inventory and Monitoring

Determining resource status is essential for planning, monitoring, and evaluation. Recent advances in remote sensing technology, in conjunction with GIS developments, provide opportunities for increasing the efficiency of resource inventory and facilitating monitoring and evaluation. Multistage sampling and analysis procedures which take advantage of the increasing resolution of satellite imagery supported by a combination of aerial photograph interpretation and field checking promise to provide resource managers with efficient methods for acquiring inventory information. These same techniques, used in conjunction with image processing procedures designed for detecting changes over time, can provide a mechanism for monitoring and evaluating the many treatments implemented on the management area. Thus remote sensing technology can go a long way toward meeting decision support needs. At the early stages of forest plan implementation this technology can provide information on current resource status and at the final stages it can be used for detecting changes in resource conditions for feedback in the monitoring and evaluation process.

Geographical Information Systems

A major enhancement in decision support software is needed in the GIS arena. It has become increasingly apparent to us that in addition to a centralized, highly technical forest-wide GIS, an independent GIS in each management unit (district office) is essential. Such a GIS should be user friendly and efficient so that individual interdisciplinary team members can explore geographical databases, generate treatment suitability models, and display the results of such models. After treatment scenarios have been developed the interdisciplinary team members should be able to use the GIS to display the future consequences of these scenarios.

Network modeling must be an essential feature of the GIS so that the ID team can deal with such problems as wildlife habitat fragmentation, wildlife travel corridors, treatment suitability, and trail and road system design.

Multiresource Simulation

A central limitation to implementing multiresource decision support systems is the lack of multiresource forest management simulation models. Currently, such software is available only for southwestern forest types (Rogers and others 1984), although it is being developed for other types.

A major stumbling block to developing such models is the lack of data needed to develop and calibrate them. Although tree growth and yield models are available for the major forest types in North America, there is a scarcity of models which predict the consequences of forest management on wildlife, recreation, watershed conditions, and range.

One promising method for developing such models from existing knowledge is the modeling workshop technique developed by Holling and Walters and their colleagues at the University of British Columbia (Holling 1978, Walters 1986). This technique, called Adaptive Environmental Assessment, brings people from a wide variety of backgrounds and with a broad mix of knowledge and talents together for brief periods of intense interaction to develop models to be used in resolving resource management problems. Participants typically include a modeling team, research scientists, resource

managers and specialists, policy analysts, decision makers, and key representatives of those groups concerned with the outcome of the decision process. The goal is to develop and test a quantitative model of the management problem within the limited time available. An example of application of this procedure to a multiresource management issue in forestry is the development of SAMM (Southeast Alaska Multiresource Management Model) by Fight and others (unpublished).

To date, few of the models developed by this technique have been used directly as decision support systems (Walters 1986, C.S. Holling, personal communication). Instead, these models have served to promote clearer thinking by, and communication among, the workshop participants about the general nature of the problems being addressed. Nonetheless, the modeling workshop approach could be used to bring together the best available knowledge about systems dynamics to develop models for forecasting the consequences of management activities.

Simulating the impact of forest management on the large number of wildlife species present poses a major challenge. However, combining a relational database with artificial intelligence technology as proposed by Patton and Severson (this volume) seems a promising approach.

Automated Goal Seeking

Once a multiresource simulation model has been used to forecast future conditions for the management unit, the next problem is reducing the vast number of possible treatment scenarios down to those which meet the overall management criteria established by the land use plan and the site specific analysis of specific issues, concerns, and opportunities. Although the most familiar mathematical programming techniques such as single objective linear programming and goal programming can be used to accomplish this task, other techniques such as multicriterion decision modeling procedures which may be more appropriate for multiresource management (Tecle and others this volume) should be explored.

Automated goal seeking software which is currently available is somewhat daunting to natural resource managers and laymen alike. What is needed is user friendly software which leads the interdisciplinary team through the construction of a multiobjective problem formulation which they can fully

understand. This module should also facilitate sensitivity analysis and other gaming with the database.

Conflict Resolution Procedures

A characteristic feature of multiresource management problems is the presence of multiple conflicting objectives that must be resolved (Fraser and Hipel 1984, Tecle and others 1988a, Tecle and others, this volume). A procedure for formulating such problems is provided in Tecle and others (1988b). This includes identifying objectives, specifying criteria, generating alternatives (or decision variables), constructing a feasible region, and determining the best solution within that region. Commercial computer algorithms are available to facilitate the evaluation process (e.g., Korhonen and Laakso 1986, Fraser and Hipel 1988). What is lacking, however, is modular integration of such algorithms into decision support systems such as TEAMS.

Flexible, integrated software for accessing, retrieving, and generating reports on database information coupled with simulation and decision models for conducting further analyses including alternative testing, sensitivity analysis, and automated goals seeking is essential for dealing with issues of the complexity facing us today in multiresource management. Supporting individual human knowledge, reasoning, and common sense of interdisciplinary teams with appropriate computer software to handle the routine, tedious tasks of analysis promises to help us improve the quality of our decisions regarding the public estate.

CONCLUSION

The rapidly exploding technology of digital electronics and software provides a promising avenue for natural resource managers to better achieve integrated forest management. These systems can support and augment human intellect, extending and amplifying mental capabilities. However, computer aided approaches must be user friendly, integrated, and understandable by those with relatively little familiarity with computers. Integrated decision support system software must be developed and implemented as soon as possible. Otherwise it seems certain that attempts at implementing forest plans will be overly time consuming, far from optimal, and difficult, if not impossible to defend.

LITERATURE CITED

- Covington, W.W., and D.B. Wood. 1988. Analyzing integrated ecosystem management opportunities in ponderosa pine. Ponderosa pine: the species and its management. Symposium Proceedings. September 29-October 1, 1987. Pullman, WA: Washington State University. pp. 165-178.
- Covington, W.W., D.B. Wood, D.L. Young, D.P. Dykstra, and L.D. Garrett. 1988. TEAMS: A decision support systems for multiresource management. Journal of Forestry 86(8):25-33.
- Covington, W.W., D.B. Wood, D.L. Young, D.P. Dykstra, J. McCarthy, and L.D. Garrett. 1987. TEAMS: a geographically based decision support system for multiresource management. GIS '87 -- San Francisco: Into the hands of the decision maker. Conference Proceedings. Falls Church, VA: American Society for Photogrammetry and Remote Sensing and American Congress on Surveying and Mapping. pp. 157-165.
- Covington, W.W., and D.B. Wood. 1989. Advancing total resource management through cooperative Native American research, development, and application. Vision of an Indian Forest Total Resource Management: Proceedings of the Conference. Warm Springs, OR: Intertribal Timber Council. pp. 225-234.
- Fight, R.D., L.D. Garrett, and D.L. Weyerman. (unpublished). SAMM: A prototype southeast Alaska multiresource model. In review.
- Fox, B.E., W.W. Covington, and D.B. Wood. (in press). Integrating computer models for forest management. In L.C. Wensel (ed.) Proceedings IUFRO Forest Simulation Systems Conference.
- Fox, B.E., M.A. Keller, A.J. Schlosberg, and J.E. Vlahovich. 1989. Opportunity costs of implementing forest plans. Environmental Management 13(1):75-85.
- Fraser, N.M., and K.W. Hipel. 1984. Conflict analysis: models and resolutions. North Holland, New York. 377 p.
- Fraser, N.M., and K.W. Hipel. 1988. Decision maker: the conflict analysis program. Waterloo Engineering Software, 22 DuPont

Street East, Waterloo, Ontario,
Canada N2J 2G9.

Holling, C.S. (ed.). 1978. Adaptive environmental assessment and management. Wiley International series on Applied Systems Analysis, Volume 3. Chichester, United Kingdom.

Jameson, D.A., M.A. Dohn More, and P.J. Case. 1982. Principles of land and resource management planning. Washington, D.C.: U.S.D.A. Forest Service. 325 p.

Korhonen, P., and J. Laakso. 1986. A visual interactive method for solving the multiple criteria problem. European Journal of Operations Research 24(2):277-287.

Patton, D.R., and K.E. Severson. (this volume) WILDHARE: A wildlife habitat suitability model for southwestern ponderosa pine.

Rogers, J.J., J.M. Prosser, L.D. Garrett, and M.G. Ryan. 1984. ECOSIM: A system for projecting multiresource outputs under alternative forest management regimes. Fort Collins, Colorado: U.S.D.A. Forest Service, Rocky Mountain Forest and Range Experiment Station. Administrative Report. 167 p.

Tecle, Aregai, M.M. Fogel, and Lucien Duckstein. 1988a. Multicriterion analysis of forest watershed management. Water Resources Bulletin 24(6):1169-1178.

Tecle, Aregai, M.M. Fogel, and Lucien Duckstein. 1988b. Multicriterion selection of wastewater management alternatives. ASCE Journal of Water Resources Planning and Management 114(4):383-398.

Tecle, A., M.M. Fogel, and Lucien Duckstein. 1988c. Choice of multicriterion decision making model for forest watershed resources management. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, General Technical Report RM-161.

Tecle, Aregai, W.W. Covington, D.B. Wood, and B.E. Fox. (this volume) Conflict resolution in multiresource ponderosa pine forest management via multiobjective decision analysis.

USDA Forest Service. 1987. Forest Service Handbook 1920. Forest plan implementation. Washington, D.C.: U.S.D.A. Forest Service.

USDA Forest Service. 1986. Working together for multiple use: Integrated Resource Management. Washington, D.C.: U.S.D.A. Forest Service. 27 p.

USDA Forest Service. 1988. Integrated Resource Management. 2nd Edition. Albuquerque, NM: U.S.D.A. Forest Service Southwestern Region. 36 p.

Walters, Carl. 1986. Adaptive management of renewable resources. New York, NY: Macmillan Publishing Company. 374 p.

Wood, D.B., B.E. Fox, and W.W. Covington. 1989. Computer-based approach for teaching multiresource management: a decision support system to aid student understanding. Journal of Forestry 87(11):11-16.

Wood, D.B., W.W. Covington, Aregai Tecle, Bruce Fox, and C. Gordon. (this volume) Use of a computer based decision support system in forest plan implementation.

Use of a Computer-Aided Decision Support System in Forest Plan Implementation¹

D. Brent Wood, W. Wallace Covington, Aregai Tecle, Bruce E. Fox, and C. Gordon²

Abstract.--A decision support system, TEAMS, has been used to develop stand-specific prescriptions for a 20,000 acre forest management area on the Navajo Reservation. A comparison of TEAMS results with those developed by conventional methods indicated that TEAMS has great potential for improving forest management decisions.

INTRODUCTION

During the past five years, the Northern Arizona University School of Forestry (NAU) has been developing a computerized decision support system (DSS) for multiresource forest management. The School designed this DSS, TEAMS (Terrestrial Ecosystem Analysis and Modeling System), to aid managers in evaluating alternatives in a multiresource environment (Covington et al. 1987 and 1988). TEAMS provides managers the ability to quickly examine the consequences of potential management alternatives. For each alternative, TEAMS provides projections of resource outputs (for instance sawtimber and forage production), economic impacts (for instance present net value and annual costs) and forest structure (for instance amounts and spatial distribution of deer cover and old growth). The system can project the consequences of a specified set of stand level management prescriptions or, given a set of goals and requirements, TEAMS will find the best combination of site-specific

prescriptions for those goals and requirements.

The version of TEAMS used in this paper combines a geographic information system (ARC/INFO), a multiresource stand simulator (ECOSIM), a linear programming optimization package (LINDO), and a graphics output display program (CHART) into a system with data handled by a geographically based relational data base management system (INFO). Linkages among these program modules have been automated; data are transferred among modules without the need for human intervention. Users provide inventory data and make decisions where judgement is required. Extensive menus and queries assist users with data input and program operation. For more information on the structure and uses of TEAMS, see Covington et al. (this volume) and Wood et al. (1989).

Following development of a prototype model, we tested it in a series of actual forest resource management applications in order to accomplish the following goals:

1. To establish whether or not projects designed using TEAMS could increase multiresource productivity;
2. To assess the usefulness and efficiency of TEAMS as a practical management tool for land management agencies; and
3. To identify and implement changes and improvements which would enhance the utility of TEAMS for assisting foresters in implementing multiresource management.

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²D.B. Wood is Professor, W.W. Covington is Professor, B.E. Fox is Assistant Professor, and A. Tecle is Assistant Professor, School of Forestry, Northern Arizona University, Flagstaff. C. Gordon is Program Manager, Research and Development Section, Navajo Forestry Department, Fort Defiance, Arizona.

To date we have completed four studies: one timber sale and two watershed management units ("10-K blocks") on the Coconino National Forest and one on a 20,000 acre compartment on the Navajo Reservation. This paper presents the results of the Navajo study.

The Navajo Study

During the fall of 1987, the Navajo Nation Forestry Department and the Northern Arizona University School of Forestry agreed to undertake a cooperative project designed to test the utility of the School's integrated multiresource decision support system as a tool for managing Navajo forest lands. The Navajo Forestry Department (NFD) is responsible for the management of over one-half million acres of commercial timber land (primarily ponderosa pine). The professional staff is charged with providing a long term annual harvest of approximately 50 million board feet to supply a tribal sawmill while maintaining amenity and traditional values important to the tribe. Although timber harvesting and processing provide important economic benefits and employment, the forests also are expected to provide forage for traditional livestock grazing, construction materials for hogans (traditional log dwellings), fuelwood, wildlife habitat, esthetics, recreation, watershed, and cultural values.

The study was conducted on a management compartment for which the NFD had recently completed a cutting plan. They had examined seven alternative plans which focused on wildlife habitat diversity, road costs, and fencing costs, as well as timber harvest volumes, economic efficiency, and sound silvicultural practices. Because TEAMS could simultaneously handle the analyses of all of these factors, project future outcomes of complex management regimes, and provide assistance in identifying an optimal regime, NFD agreed to participate in an analysis of the area using the decision support system. This cooperative effort offered an unprecedented opportunity to compare a decision support system with conventional methods.

METHODS

The study entailed using TEAMS to identify, evaluate, and compare a variety of alternatives for managing a compartment within the commercial ponderosa pine area of the Navajo

reservation. It consisted of four phases:

1. Selection of a study area and specification of goals for the area;
2. Modification of the system to reflect Navajo conditions and requirements;
3. Generation and analysis of alternatives; and
4. Comparison of the selected TEAMS alternative with an alternative developed by NFD using conventional methods.

Study Area

The area selected for analysis by NFD was Compartment 19, a 20,000 acre block of ponderosa pine on the Defiance Plateau north of Fort Defiance, Arizona. Compartment 19 contains 96 stands most of which are two-storied. Overstories are predominantly overmature yellow pine (large, old ponderosa pine) with understories generally consisting of immature pine with relatively low densities. The area is a mesa, with most of its acreage on the flat top. Most of the steep slopes bounding the mesa are inoperable for harvesting. Site quality varies from poor to good. A complete set of recent inventory data was provided by NFD and used in the analysis.

The Department's overall goal for Compartment 19 was to maximize present net value subject to the following requirements:

1. A minimum of 15 percent of the compartment was to be maintained in old growth primarily for wildlife habitat;
2. All stands infected with dwarf mistletoe were to be harvested during the first entry;
3. Archeological sites were to be buffered from harvest activity;
4. A minimum harvest of 28 million board feet was required in the first entry;
5. A minimum harvest of 50,000 poles was required during each entry;
6. No harvesting was to occur on slopes exceeding 40 percent; and

7. Wildlife habitat diversity was to be improved with deer as a featured species.

System Modifications

Modifications to TEAMS were required to make it compatible with the unique conditions and management situation faced by NFD. These were implemented in two stages. First, after becoming familiar with the existing procedures and assumptions of TEAMS, NFD developed a preliminary list of needed revisions. NAU incorporated the revisions, executed a preliminary series of TEAMS runs based on the initial set of goals and requirements, and presented the results to NFD in March, 1988. Second, working together, NFD and NAU carefully evaluated the outputs and identified additional system modifications to enhance its utility in evaluating alternatives. Such testing and modification continued until we were satisfied that the system was providing the information required for assessing outcomes according to Navajo criteria.

System modifications were of three general types. First, values and costs specific to the Navajo Nation were substituted for those then in the system. New cost categories were also added for pole marking and for fencing regenerating stands. Poles are provided free of charge for hogan construction, but because of heavy demand, harvest must be closely regulated to avoid degradation of the timber resource. Heavy grazing by sheep, an activity of great traditional importance to the Navajo people, could result in nearly total seedling loss without protection. Because there is no market for pulpwood in the area, pulpwood outputs were eliminated.

Second, stand level treatment alternatives were modified to reflect NFD practices. We altered shelterwood alternatives to conform to NFD silvicultural standards and added thinning alternatives with lower residual basal areas than the existing version of TEAMS was simulating. The model was also altered to encompass three 20-year periods reflecting the 20-year reentry cycle employed by NFD.

The third type of modification involved adding new outputs and growing stock provisions which could be projected, constrained, and displayed along with original outputs. These included pole harvests and standing poles (required for hogan construction), area

standards for old growth, number of snags, and future diameter distributions. NFD also requested additional GIS plots showing the locations, types, and times of treatment for each alternative because of concerns for harvesting and transportation efficiency.

Alternative Analysis

Following system modification, the TEAMS analysis began with two baseline runs: one in which no timber harvesting was allowed and another in which present net value was maximized without any other constraints or requirements. Comparison of these runs to constrained ones enabled us to analyze the tradeoffs imposed by requirements for such things as timber harvest level and wildlife habitat. We next added a set of constraints reflecting NFD's initial specification of goals and requirements for the compartment. After TEAMS was run, NFD analyzed outputs, tradeoffs, and opportunity costs associated with these constraints and identified problems and opportunities for improvement.

A number of problems were identified upon examining results of the initial alternative specified by the Department. First, the 15 percent old growth requirement could not be achieved until the third entry of the analysis period. An insufficiency of current old growth and time needed to achieve old growth conditions prevented meeting the requirement. Nothing could be done to eliminate this problem. Second, when compared to the unconstrained maximum PNV run, meeting all of the NFD requirements created an opportunity cost of over \$2.7 million. Third, the level of harvest in the first entry exceeded the maximum capacity, 50 million board feet, of the Navajo sawmill. Finally, at the end of the 60 year analysis period, the pole inventory had dropped to near zero. Because continuity in the availability of hogan construction materials is important to the Navajos, this was unacceptable.

Given the results of the first analysis, the linear programming formulation was altered. The excessive sawtimber harvest was prevented by constraining the harvest to a maximum of 50 million board feet. Although this nominally reduced present net value, harvests over this amount could not be utilized and, in reality, would contribute nothing to PNV.

Further analysis showed that opportunity costs could be materially reduced by scaling down old growth requirements and eliminating constraints which would require treatment of mistletoe infected stands in the first entry. Although other requirements generated opportunity costs, only these were deemed discretionary by NFD. Old growth requirements for the first two entries had previously been reduced in order to achieve a feasible solution. The third period requirement, however, still had a significant effect on management and generated high opportunity costs. Reducing the old growth requirement from 15 percent to 10 percent of the total area increased present net value by over \$700,000.

Mistletoe infections are ordinarily treated as rapidly as possible through regeneration harvests or heavy thinning of infected trees. Because of the surprisingly high opportunity costs entailed in early treatment (\$240,000) and the relatively minor degrees of infection within the compartment, NFD concluded that treatment could be delayed in most cases. Mistletoe treatment constraints were altered accordingly.

Finally, we added a constraint requiring an ending inventory of 500,000 poles following the third and final entry. This constraint did not affect the quantity of poles harvested during the three entries, as feared, but did result in prescriptions which produced more poles.

After making these changes another TEAMS analysis was run and outputs were presented to NFD. After examination, a new list of potential adjustments was

compiled and analyzed. This process continued through several iterations. With each succeeding iteration the magnitude of adjustments became smaller and smaller until solutions converged on an alternative which could not be materially improved.

Following the TEAMS analysis described above, NFD provided a complete accounting of prescriptions for stands within Compartment 19 which had been developed independently. These were translated as accurately as possible into the treatment categories employed by the TEAMS system and constraints were written for each stand to "force" TEAMS to select and simulate the NFD prescription as closely as possible.

RESULTS

In discussing results we concentrate on comparisons between the alternative finally selected using TEAMS and the alternative developed independently by NFD.

The silvicultural prescriptions elected using TEAMS differed substantially from those specified by NFD. Table 1 shows that, without TEAMS, NFD had prescribed a much higher proportion of shelterwood harvests than they did using TEAMS. NFD called for shelterwood harvests on nearly half of the compartment (9,424 acres) whereas only about 1300 acres would be regenerated with the TEAMS alternative. Most of the NFD regeneration harvests (6000 acres) were scheduled for the first entry. Because of low stocking rates in many of the stands, NFD reasoned that it would be beneficial to regenerate

Table 1. Summary of silvicultural prescriptions for TEAMS and NFD.

Treatment	Period 1		Period 2		Period 3	
	NFD	TEAMS	NFD	TEAMS	NFD	TEAMS
----- (acres) -----						
Overstory						
Harvest only	4527	5821	--	8249	5002	925
With thinning	1473	3628	196	143	--	--
Total overstory harvests	6000	9449	196	8392	5002	925
Shelterwood						
Seed cut	7093	409	2331	800	--	97
Final removal	--	--	7093	409	2331	800
No harvest	-----		1025	1952	-----	

as soon as possible in order to increase their productivity, a standard practice. Shelterwood harvests, however, entail leaving a high proportion of the largest trees as a seed source for a 20-year period and generate costs for site preparation and fencing. It was economically better to harvest the overstories immediately and to delay regeneration until the understories reached maturity. The TEAMS analysis showed that losses in overstory value (primarily because of discounting) and high regeneration costs overshadowed values associated with restocking the stands. The two alternatives also differed markedly in the acreage left unharvested. With TEAMS, nearly 10 percent of the compartment would not be harvested, nearly double the unharvested area prescribed by NFD.

Table 2 shows resource outputs and conditions projected by TEAMS for the NFD and TEAMS alternatives. Entries were simulated in Years 1, 21, and 41; activities in Year 61 were limited to final removals on acreage receiving a seed cut in Year 41. Outputs reflect post-harvest conditions.

Volume harvested was higher for TEAMS in the first entry but lower in the second two; total volume harvested was higher for NFD. The numbers and distributions of trees projected for the end of the analysis period (Year 61) were as follows:

Dia. class	NFD	TEAMS
---(in)---	---1000's of trees---	
< 5	473	87
5-12	1122	509
12-16	360	967
16+	116	291

In that year the TEAMS alternative would produce nearly 300,000 mature trees (greater than 16-inch DBH), a number more than sufficient for another sawtimber harvest entry (for comparison, there are currently 238,000 trees of that size in the compartment) whereas the NFD alternative would yield only about one-third that number, too few for harvest given economic considerations and multiresource concerns. NFD produced more poles in the ending inventory.

NFD pole harvests were substantially higher than those yielded by TEAMS during

Table 2. Comparison of results from TEAMS and NFD alternatives.

	Year			
	1	21	41	61
Sawtimber harvest (Mbf)				
NFD	38,059	53,960	33,440	--
TEAMS	50,000	44,675	15,785	198
Pole harvest (1000's)				
NFD	226	207	--	--
TEAMS	50	50	50	--
Forage (AUM's)				
NFD	526	712	908	864
TEAMS	526	572	615	568
Water (ac.ft.)				
NFD	233	250	367	333
TEAMS	233	217	233	183
Deer cover (ac)				
NFD	4,842	5,898	6,733	8,298
TEAMS	6,406	10,221	11,429	13,919
Old growth (ac)				
NFD	--	--	172	185
TEAMS	--	905	2,165	2,735
Costs (\$1000's)				
NFD	1,213	1,094	544	--
TEAMS	876	775	296	3
Net cash (\$1000's)				
NFD	3,859	6,384	4,054	--
TEAMS	6,052	5,356	1,812	18
Present net value (\$1000's)				
NFD	-----	8,190	-----	-----
TEAMS	-----	10,130	-----	-----

the first two entries but fell to zero in the third entry (table 2). TEAMS, however, provided the minimums specified by NFD for all three entries. NFD considered the continuation of harvest into the third period a benefit and determined that the lower harvests in the first two entries would be balanced by economic gains. Increasing pole harvests would have been expensive in terms of marking and administrative costs as well as limiting opportunities for more profitable management alternatives.

Although both NFD and TEAMS produced increases in forage yields (table 2), those for NFD were substantially higher. Water yields for TEAMS declined in some periods and were lower than those projected for NFD in all but the first period (table 2). Although high levels of forage and water were considered desirable, when tradeoffs in economic values and provision of other resources were considered, NFD judged the smaller yields reasonable. Achieving higher levels would entail substantial economic costs in timber management, deplete growing stock available for future harvests, degrade deer habitat, and nearly eliminate old growth.

Deer habitat is currently limited because of insufficient cover acreage. Cover would remain inadequate with the NFD alternative whereas TEAMS produced a significant increase (table 2). Figures 1 and 2 show the spatial distribution of forage and cover in Year 21 for NFD and TEAMS, respectively. TEAMS not only provided more cover than NFD but distributed it more evenly across the compartment. (With TEAMS, the user may specify constraints which require cover

distribution.) Although the Navajo plan produced more forage, another important component of deer habitat, abundant forage will not be utilized when adjacent cover is lacking. Old growth, which is important for other wildlife species, would be minimal under NFD but was substantially increased (to meet Navajo goals) with TEAMS.

Finally, TEAMS produced a substantially higher present net value (PNV) than did NFD. PNV for the compartment with TEAMS was \$10.13 million, an increase of almost 24 percent over the NFD's \$8.19 million PNV. There are three major reasons for the increase. First, costs were substantially lower in all three entries (table 2). This was due to lower regeneration costs (fencing and site preparation) and lower pole harvest administration costs. Second, although NFD prescriptions resulted in a higher total net revenue during the planning period, despite higher costs, first entry net revenue was considerably higher for TEAMS (table 2). After discounting future net revenues at 4 percent, TEAMS provided a substantial economic advantage. Finally, ending inventory value, a factor included in PNV calculations, was greater for TEAMS because of the much higher proportion of valuable mature trees remaining at the end of the planning period.

DISCUSSION

Conducting an area analysis on a large multi-stand compartment using conventional methods is a highly complex, tedious, and time-consuming process. Such analyses typically require months of



Figure 1.--Spatial distribution of deer cover and forage in year 21 for NFD prescriptions.

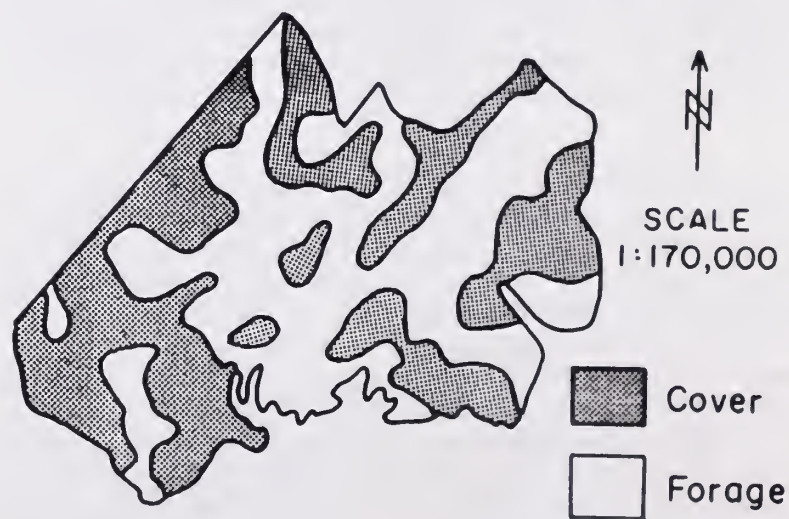


Figure 2.--Spatial distribution of deer cover and forage in year 21 for TEAMS prescriptions.

work and ordinarily only four or five alternatives can be evaluated. Furthermore, it is generally impossible to forecast long-term or cumulative effects in such alternative analyses. At best, planners are only able to assess immediate post-treatment impacts. The complex dynamics of forest ecosystems and vast amounts of information that must be processed make forecasting multiresource impacts exceedingly difficult with conventional computer support. Long term analyses are usually limited to the timber resource and, very often, such analyses employ aggregated data so that results lack spatial definition. Given these difficulties, planners and managers are forced to rely on standards and guidelines which prescribe activities which may and may not be implemented. Rotation limits, adjacency rules, density standards, and regeneration requirements, for example, are imposed in hopes that they will result in desired future conditions. It would indeed be fortuitous if such planning resulted in an optimal solution.

As demonstrated in the Navajo project, computerized decision support systems such as TEAMS can solve many of these problems. First, a large number of alternatives can be analyzed in a relatively short period of time. Over 30 alternatives were tested during this project before arriving at a final decision. The average amount of time spent in computer input and processing was less than an hour per alternative. Furthermore the linear programming element used in the DSS approach allows users to converge quickly on the feasible decision space so that time is not wasted on the nearly limitless number of unacceptable alternatives. Two or three base runs can establish the bounds of possibility for the most important resources. Using TEAMS appears to materially reduce the total time required to formulate and analyze alternatives.

Although initial inventory data entry and digitizing are time-consuming, data acquisition was facilitated in this project because much of the necessary data had been computerized and spatial data digitized by NFD prior to the inception of the project. Transferring and reformatting these data were accomplished through simple computer routines. Because computerized databases are so commonly used by land management agencies, our experience with the NFD should not be considered unusual. Other data, however, had to be extracted from various Department records and hand-entered to the system. Because data

requirements are similar for conventional and DSS methods, data acquisition and compilation costs probably do not differ greatly. The real advantage with DSS is its ability to utilize the data more efficiently and productively.

Second, DSS technology allows an efficient incremental approach to decision-making. With this project, we found that each alternative tested revealed problems and opportunities which led to ideas for formulating the next one. Our knowledge of tradeoffs grew with each iteration and by the time we were through experimenting we felt confident in our decision. This approach, we believe, is likely to lead to better decisions than would formulating several discrete alternatives in advance and testing each independently, a common practice. Resource managers commonly fear that utilization of complex computer software will replace professional judgement and experience and cause them to lose control of planning and decision-making processes. We found the opposite to be the case; TEAMS greatly increased opportunities for experimentation and creativity. Instead of depending upon accepted conventions, we were able to examine and evaluate innovative management strategies. Each member of the planning team had the opportunity to try out his ideas.

Third, the multiresource simulation feature of TEAMS allowed us to both examine and constrain the long-term effects of management actions. Projections of future resource outputs and forecasts of both quantitative and spatial elements of forest structure were provided by the system. We were able, for example, to determine that the ending inventory of poles was insufficient to meet future needs and subsequently to add a constraint to ensure that these needs were met. Likewise, we were able to ensure that old growth requirements were met, insofar as possible, both throughout the analysis period and within the ending inventory in the most economical manner.

Finally, the system provided a wide array of information in easily interpreted graphic and map formats similar to the figures provided in this paper. Results from up to four alternatives at a time could be displayed and compared, resource by resource, on a single graph or map set making tradeoff analyses simple.

We are convinced that decision support systems like TEAMS have great

potential for improving multiresource management on Navajo forests as well as other ownerships. However, we also recognize the limitations of the system. The primary result expected from this study was, in fact, a list of problems and needed improvements. We were less concerned with the absolute results than with making TEAMS more useful to managers.

Several needs were identified. First, resource response functions (for projecting resource outputs) need to be calibrated for local conditions. We felt that those currently in the system were sufficiently accurate to demonstrate usefulness but that localization could improve reliability. Multiresource simulation models also need to be developed for other forest types; a model for pinyon-juniper woodlands, which are particularly important to the Navajos, is currently in initial stages of development.

Second, methods need to be developed for dealing with heterogeneity within stands. The simulation models within TEAMS assume homogeneity. Some stands within the study area, however, were diverse enough that a common treatment could not logically be applied to the entire stand. For example, some stands contained dense clumps of young trees as well as patches consisting only of mature timber. These situations, which occurred relatively frequently on the study area, were reflected in NFD prescriptions which specified thinnings in the former and regeneration harvests in the latter. These options could not be directly simulated by TEAMS and hence unrealistic prescriptions resulted. Possible solutions range from subdividing such stands into more homogeneous elements prior to the analysis, to making post-analysis adjustments where necessary. Experimentation is needed to determine the best approach.

Third, the DSS must be customized for particular applications and users. The Navajos, for instance, required a continuing supply of poles. Providing sufficient flexibility within the model to make it universally applicable would be essentially impossible. Fortunately, the modular design of TEAMS makes such changes relatively simple.

Fourth, methodology is needed for coordinating the management of a compartment in time and space with the forest unit of which it is a part. Optimizing each compartment in isolation will seldom, if ever, result in optimal

management for the forest as a whole. On the other hand, comprehensive, long-term forest planning on a site-specific basis is clearly impractical, and probably impossible, with current technology. The NFD, like other agencies, must currently rely on subjective, intuitive techniques for bridging the gap between long term strategic planning and project level implementation. The Navajos, for example, have established an annual sustainable harvest of approximately 50 million board feet through their long term planning process. Once general harvest locations are established, a DSS like TEAMS can help to develop optimal site-specific strategies for attaining harvest targets and meeting other multiresource goals within the selected compartment(s). Determining the sequence in which compartments should be entered over time (i.e., which compartments should be entered in years 1, 2, 3, 4, etc.), however, is an important issue. An intermediate level of planning, we believe, is needed to establish this order of entry based on such things as economic efficiency, interactions among compartments, and transportation system development.

Finally, to be of maximum utility to managers and planners, the system must be usable with a minimum of technical training. Much efficiency and creativity is lost when analyses must be routed through and interpreted by a computer expert. We have designed TEAMS with this goal and many of its capabilities can be accessed with relative ease. Other features like most contemporary geographic information systems, however, still require substantial technical expertise. System operation needs to be simplified before it can be utilized without technical support by agencies like NFD.

FUTURE PLANS

Based upon the promising results of this study, the School of Forestry and the Navajo Forestry Department have jointly developed a proposal designed to solve the problems and implement the improvements we have identified. The project, which we expect to begin in 1990, is designed to provide a DSS based, hierarchical forest planning system for the Navajo Nation. The system will be designed to incorporate Navajo goals, requirements, and constraints and will encompass all major forest and woodland ecosystems within the Navajo Reservation. The proposal also provides for training

in DSS use and NFD ownership of all necessary hardware and software. We believe that the DSS technology developed during this project will be adaptable to other ownerships and forest types.

LITERATURE CITED

Covington, W. W., D. B. Wood, D. L. Young, D. P. Dykstra, J. McCarthy, and L. D. Garrett. 1987. TEAMS: A geographically based decision support system for multiresource management. P. 157-165 In GIS '87 -- San Francisco. Proceedings of the second annual international

conference on geographic information systems. American Society for Photogrammetry and Remote Sensing and the American Congress on Surveying and Mapping, Falls Church, VA.

Covington, W.W., D.B. Wood, D.L. Young, D.P. Dykstra, and L.D. Garrett. 1988. TEAMS: a decision support system for multiresource management. *Journal of Forestry* 86(8):25-33.

Wood, D.B., B.E. Fox, and W.W. Covington. 1989. Computer-based approach for teaching multiresource management. *Journal of Forestry* 87(11):11-16.

The Effect of Planning Unit Size on Implementing Forest Plans¹

Bruce E. Fox, D. Brent Wood, W. Wallace Covington, and Aregai Tecle²

Abstract: The pattern and magnitude of resource flows over time, as well as the direct and opportunity costs, associated with implementing forest plan standards and guidelines at an operational, on-the-ground level, may depend on the size of the planning units under consideration. As a preliminary examination of this problem multiresource analyses were performed on different sized planning units within the same ponderosa pine dominated watershed in northcentral Arizona, using a computer aided decision support system. Results of these analyses are reported, as well as a preliminary assessment of the relative efficiencies, opportunity costs and tradeoffs associated with implementing forest plan standards and guidelines for different sized planning units.

INTRODUCTION

The National Forest Management Act of 1976 (NFMA) required detailed planning on all National Forests, with the objective of managing the forests to provide for multiple use and sustained yield in the production of goods and services from the forests while at the same time accounting for the environmental impact of management as required by the National Environmental Policy Act of 1969. As a result of the passage of the NFMA, the planning process required for the USDA Forest Service has increased in complexity.

This increased complexity stems from many sources, including requirements for public involvement in the development of forest plans, the use of intricate computer-based planning models, the development of detailed standards and guidelines for management, and provisions in the planning process for monitoring outputs over time. Forest plans have been written for each National Forest, and are beginning to be implemented. This implementation requires the disaggregation of forest level output targets, and the development and application of management treatments to specific units of land.

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² Bruce E. Fox is Assistant Professor, D. Brent Wood and W. Wallace Covington are Professors, and Aregai Tecle is Assistant Professor, School of Forestry, Northern Arizona University, Flagstaff, AZ.

Given individual forest based plans, a decision is required as to the appropriate size of a unit of forest land on which to apply forest plans. This decision depends on planning scope and objectives and the particular type of resource under consideration. For timber management, the appropriate sized unit might be an individual stand, a group of timber stands, a watershed, a district, or the entire forest. For wildlife management, the size of a planning unit depends both on the wildlife species under consideration, the characteristics of its habitat, and the spatial distribution of this habitat. A watershed planning unit

could vary from a first order drainage to a major river basin. Likewise, a recreation planning unit could be relatively small and very specific, such as a developed recreation site, or large and fairly general, such as a wilderness area. Economic considerations also influence such disaggregation decisions. For example, the costs of developing transportation and harvesting systems can vary greatly with the size of the planning unit (Davis and Johnson 1987).

In timber management the individual timber sale has long been the traditional unit for implementing forest plan management activities. However logical for timber harvesting, timber sales are not necessarily the appropriate size unit for managing and monitoring the impacts of specific management treatments on other forest resources. In an attempt to address the issue of planning and monitoring units that can vary by resource, the Southwestern Region of the Forest Service (Arizona and New Mexico) is considering a number of options. Some analyses are still being carried out at a timber sale level, while others are being conducted on multi-sale areas commonly known as "10-K Blocks."

A 10-K Block is a contiguous unit of land, approximately 10,000 acres, that is defined by watershed, topographic, or administrative boundaries. Blocks can contain multiple timber sale areas, and sale boundaries may overlap Block boundaries. Forest wide management standards and guidelines are to be applied on each 10-K Block during the implementation process. Planning on 10-K Blocks is driven by the need to achieve Forest Plan resource output targets while adhering to Plan standards and guidelines. In commercial forest types, timber sale activities often serve as the catalyst for planning and implementation efforts.

Previous work in the area of the hierarchical nature of ecological systems, and the effect of hierarchies and planning unit size on Forest Plan implementation, has received considerable attention. Descriptions and discussions of the hierarchical nature of landscapes can be found in Allen and Starr (1982), Allen and others (1984), and Naveh and Lieberman (1984). Concerns over the impact of the hierarchical nature of forest systems, both ecological and organizational, on the Forest Planning process has been raised by numerous authors (Cortner and Schweitzer 1983, Keller 1986, Ryberg and

Gilbert 1986, Armel 1986, Merzenich 1986, Milne 1987, and Schugart and Gilbert 1987). The effect of planning unit size on potential timber output levels has been discussed by Hrubec (1976).

Examples of implementing Forest Plans have focused on both methodologies (Ryberg and Gilbert 1986, Dykstra 1987) and the effect on resource outputs when applying Forest level standards and guidelines to a specific land area (Fox and others 1989). The objective of the research reported here was to integrate the concerns about the hierarchical nature of forest systems by comparing resource outputs over time when Forest Plan targets are disaggregated to two different sized planning units, the individual timber sale and a 10-K Block.

METHODS

Accomplishing the research goals required a three step research procedure:

1. Identification of a 10-K Block study area that contained multiple timber sales;
2. Analysis of resource outputs over time for the entire 10-K Block; and
3. Analysis of resource outputs over time for individual timber sales within the 10-K Block.

Study Area

The Bar M 10-K Block on the Mormon Lake Ranger District of the Coconino National Forest in northcentral Arizona was chosen as the study area. This site was chosen for analysis for three reasons. First, inventory data for the Block were relatively recent and complete, aiding in the analysis. Second, the Forest Service had scheduled timber sales and generated output targets for the Block. And third, the arrangement of timber sales within the Block lent itself to a fairly straightforward comparison between outputs for the Block as a whole and the sum of the individual timber sales.

This 10-K Block located 30 miles south of Flagstaff, Arizona, contains 15,901 acres of primarily ponderosa pine forest (fig. 1). The Block has gently rolling terrain overall, but with steep slopes along drainages with

intermittent streams. Elevations in the Block range from approximately 6,500 to 7,500 feet.

At the time this analysis was conducted, the Bar M 10-K Block included five timber sales. Four of these sales, Bar M, Broliar, Cracker, and Long, are totally contained within the Bar M 10-K Block. Only 1,276 of the 5,184 total acres of the fifth sale, Tie, is contained within the Bar M Block, with the remaining acres of this sale in an adjoining 10-K Block. The Bar M 10-K Block is subdivided into 401 individual stands ranging from 2 to 285 acres. Site indices range from less than 47 to over 90. Timber volumes per acre range from 0 in open meadows and parks to over 37 thousand board feet (MBF) (table 1). No timber has been cut in the Block for over 40 years.

Since only part of the Tie Sale is located within the Bar M 10-K Block, the targeted harvest for this sale (13 MMBF) was not included in the analysis. To prevent harvesting in the Tie Sale area from contributing to the overall Block timber output, constraints were specified to prevent harvesting in all stands in the Tie Sale. Other resource outputs from the Tie Sale that would

occur in the absence of harvesting were allowed to contribute to overall output totals, however. All non-timber outputs for the Tie Sale were also included in the combined totals for the individual sales to insure comparability between the individual sale and 10-K Block analyses.

Only general Forest Plan standards and guidelines were considered in this analysis. Specific issues, concerns, and opportunities associated with the Bar M 10-K Block, such as Spotted Owl habitat, were not considered in this analysis.

10-K Block Analysis

The multiresource analyses of alternative management prescriptions for both the Bar M 10-K Block and the individual timber sales within the Block were accomplished using TEAMS (Terrestrial Ecosystem Analysis and Modeling System), a decision support system developed by the School of Forestry, Northern Arizona University. TEAMS combines a geographic information system (GIS), a multiresource stand simulator, a linear programming optimization package, and a graphics output display program into an integrated information processing and retrieval system, all organized around a data base management system (Covington and others 1988). TEAMS allows for a relatively rapid analysis of various alternative management scenarios, with the goal of achieving an optimal solution to a given management problem. The version of TEAMS used in this analysis allows for planning and analysis over a forty year planning horizon.

The majority of the inventory data necessary for this analysis was provided by the Forest Service. For each stand, these data included stand boundaries, site index, and stand tables. A field inventory conducted by School of Forestry faculty and students generated the remaining data.

Inventory data were entered into the database, and all stand boundaries were digitized and entered through the GIS. Once the data were entered, the multiresource simulator was run to project the resource flows and stand conditions over time associated with a variety of silvicultural alternatives for each stand in the Block. Constraints were entered to mimic Forest Plan targets, standards, and guidelines. First, stand-specific constraints were written to prevent timber harvesting in

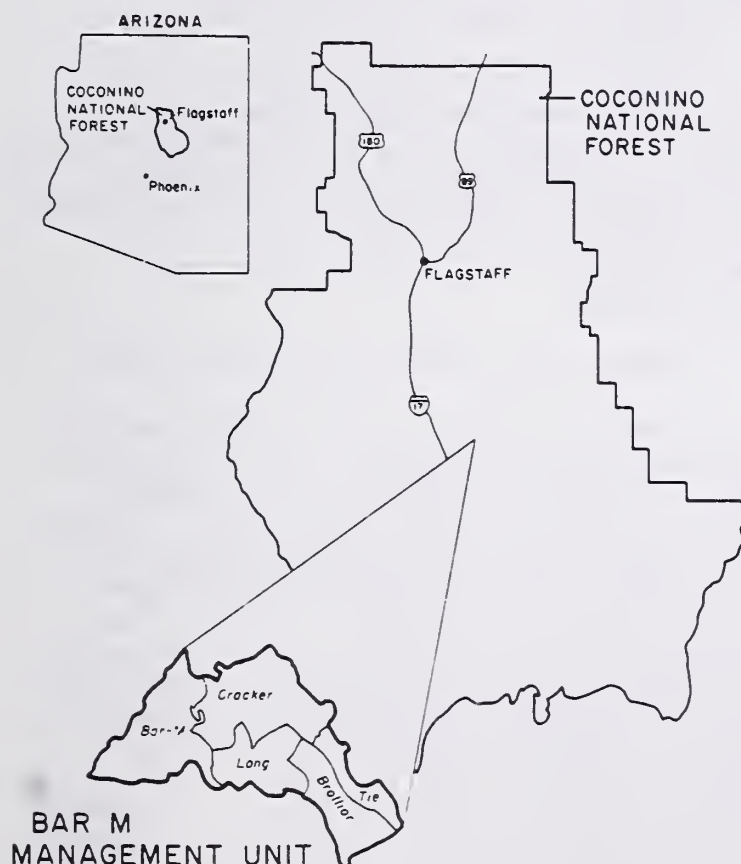


Figure 1: Location of Bar M 10-K Block and individual timber sales

Table 1: Timber sale characteristics by sale area and total unit, Bar M 10-K block planning unit

Sale Area	Acres	Number of Stands	Stand Size (Ac)		Site Index	
			Min	Max	Min	Max
Bar M	4,627	108	3.5	177.4	47	90
Brolliar	2,624	58	2.0	285.0	53	89
Cracker	4,785	121	2.9	143.3	43	93
Long	2,589	77	2.8	242.0	52	90
Tie	1,276	37	2.6	150.0	53	89
BLOCK	15,901	401	2.6	285.0	43	93

Sale Area	Board Foot Volume per Acre				Coefficient of Variation
	Min	Max	Ave	Standard Deviation	
Bar M	0.0	32,034	7,639	5,011	65.6
Brolliar	0.0	22,150	10,232	6,577	64.3
Cracker	0.0	37,843	8,711	5,933	68.1
Long	0.0	20,462	8,903	5,725	64.3
Tie	0.0	17,594	8,329	4,878	58.6
BLOCK	0.0	37,843	8,644	5,698	65.9

all areas identified as having steep slopes. These areas were identified using the GIS capabilities of TEAMS. Although timber harvesting was prohibited, other resource values from these acres were included in the output.

Second, Forest Plan timber harvest targets were entered as constraints to the system. The total targeted timber harvest for the Bar M, Brolliar, Cracker, and Long sales, 36.3 MMBF, was added as the required sawtimber harvest during the first decade (Year 1) of the planning period. These targets were generated based on current stand volumes, aggregated first to the timber sale, and then to the entire Block. In addition, timber harvest constraints totalling 10 MMBF for Years 11 and 21 of the planning period were entered. These constraints were included to help insure long term availability of harvestable timber by requiring that timber volume is available for at least the second and third decades.

Third, Forest Plan standards and guidelines for acres of old growth and elk habitat were added. Initially, an old growth requirement was set at 5% of the Block (795 acres) beginning in Year 11. To force the provision of elk cover throughout the planning period,

constraints were written to require that at least 30% of the Block be in conditions to provide elk cover throughout the planning period.

Once all constraints were entered, the linear programming optimization module was used to select from among the various silvicultural alternatives the set which would maximize the present net value of the Block while still meeting Forest Plan standards and guidelines.

Individual Timber Sale Analyses

The same basic procedures used for the 10-K Block analysis were followed for the analysis of each individual sale. Separate data bases were created from the overall Block data base to facilitate the analysis. The timber harvest targets shown in table 2 were entered for each sale. As noted above, these targets were generated based on current stand volumes, aggregated for each individual timber sale. The 10 MMBF maximum timber harvest levels in Years 11 and 21 were allocated to each sale proportional to its initial timber sale target. Slope constraints were added to each sale. Old growth targets were added to each sale to equal 5% of each sale area, beginning in Year 11. Elk cover constraints were added as for the entire 10-K Block.

In addition, the mean and variance of the volume per acre for each sale were compared to those of the Block as a whole to determine if there existed a statistically significant difference between these values, as a measure of relative homogeneity.

RESULTS

10-K Block Analysis

With all constraints in place, the initial run for the Bar M Block proved infeasible, due to the size of the old growth constraint for Year 11. A feasible solution was obtained only when the Year 11 constraint was reduced to 667 acres (4.2% of the Block), the maximum attainable old growth acres for that date. Old growth constraints were not binding in subsequent years.

Table 3 displays the outputs for the entire Block. Timber sale targets were met in each period, and except for Year 11 old growth, all other targets were achieved. Forage production during the analysis period ranged from a low of 727 Animal Unit Months (AUM's) in Year 41 to a high of 828 AUM's in Year 11. Incremental water yields ranged from a low of 238 acre feet above baseline flows in Year 21 to a high of 278 acre feet above baseline in Year 1, immediately following timber harvest activities. The present net value of this alternative, from timber harvesting, AUM's, and the value of the standing timber inventory, totaled \$10,680,696, at a discount rate of 4%.

Table 3: Resource output comparisons: Entire Bar M 10-K Block and the sum of timber sales within the 10-K Block

Resource Output	Total for 10-K Block	Total for Individual Sales
Present net worth (\$)	10,680,696	10,617,862
Sawtimber harvest (MMBF)		
Year 1	36.3	36.3
Year 11	10.0	10.0
Year 21	10.0	10.0
Year 31	1.031	0.396
Old growth (acres)		
Year 1	560	532
Year 11	667	639
Year 21	1,562	1,137
Year 31	2,570	2,759
Year 41	2,629	2,877
Forage production (AUM's)		
Year 1	740	738
Year 11	828	833
Year 21	751	754
Year 31	35	738
Year 41	727	717
Incremental water yields (acre-feet)		
Year 1	278	278
Year 11	265	274
Year 21	238	241
Year 31	251	250
Year 41	265	246

Individual Timber Sale Analyses

Initial runs for three of the four individual timber sales, Bar M, Broliar, and Cracker, proved infeasible due to the old growth constraint in Year 11. The maximum attainable old growth in Year 11 ranged from a low of 1.9% (92 acres) for the Cracker Sale to the full 5.0% (129 acres) for the Long Sale. Based on individual sale analyses, the maximum combined old growth achievable totaled 539 acres, 3.4% of the total area of the Bar M 10-K Block.

All other constraints were achieved for all sales, including providing a minimum of 5% of the Block in old growth after Year 11 of the analysis. The specified elk cover requirement was achieved in every period of the analysis. Sawtimber harvest levels were met for Years 1, 11, and 21. Combined forage production during the analysis

Table 2: Targeted timber harvest by timber sale, Bar M 10-K block

Sale Area	Timber Harvest [MBF]
Bar M	12,000
Broliar	3,300
Cracker	11,000
Long	10,000
Tie	N/A
Total	36,300

period ranged from a low of 717 AUM's in Year 41 to a high of 833 AUM's in Year 11. Combined incremental water yields ranged from a low of 241 acre feet above baseline flows in Year 21 to a high of 278 acre feet above baseline in Year 1, immediately following timber harvest activities (table 3). The total present net value of all five individual timber sales, again using a 4% discount rate, was \$10,617,862.

The mean volume per acre for each sale was tested against the mean value for the entire Block, using the procedures for comparing a single mean to a specified value (Montgomery 1984). The variance in volume per acre for each individual sale was also compared to the overall Block variance using standard F-test procedures (Montgomery 1984). These results are shown in table 4. Only the mean volume per acre for the Bar M Sale was statistically different from the overall Block volume, at the 5% level. None of the variances of the individual sales were significantly different from the overall Block variance, again at the 5% level.

Table 4: Statistical Comparison of Individual Sale and Block Mean Volumes per Acre and Variances of Volume per Acre

Sale	Calculated ²	SALE CHARACTERISTIC		
		Test of Mean ¹ Test ³	Test of Variance ⁴ Calculated ⁵	Test ⁶
Bar M	-2.084	2.00	0.773	1.32,.75
Brolliar	1.839	2.021	1.332	1.32,.75
Cracker	0.164	1.980	1.084	1.22,.82
Long	0.397	1.980	1.009	1.32,.75
Tie	-0.393	2.042	0.733	1.46,.68

NOTES:

$$^1H_0: u = u_0$$

$$^1H_1: u \neq u_0$$

Where: u is the average volume per acre for each sale and u_0 is the overall average volume per acre for the Block.

$$^2t_0 = (y - u_0) / [s / n^{0.5}]$$

Where: y = average volume per acre for each sale
 u_0 = average volume per acre for Block
 s = standard deviation of individual sale volume
 n = number of stands in an individual sale

$$^3t_{\alpha/2, n-1}$$

Where: $\alpha = 0.05$

$$^4H_0: \sigma_1^2 = \sigma_2^2$$

Where: σ_1^2 = variance in individual sale volume

$$^4H_1: \sigma_1^2 \neq \sigma_2^2$$

σ_2^2 = variance in Block volume

$$^5F_0 = s_1^2 / s_2^2$$

Where: s_1^2 = variance in individual sale volume

s_2^2 = variance in Block volume

$$^6F_{\alpha/2, n1-1, n2-1}$$

$$1/F_{\alpha/2, n1-1, n2-1}$$

Where: $\alpha = 0.05$
 $n1$ = degrees of freedom in numerator
 $n2$ = degrees of freedom in denominator

DISCUSSION AND CONCLUSIONS

Little difference exists between the total outputs or the timing of resource flows generated in the total Block or individual sale analyses (table 3 and fig. 2 and 3). Although the present net value for the analysis of the entire Bar M Block was higher than the sum of the present net values for the individual sale alternatives, the difference was less than 1% of the total present net value for the Block. Sawtimber targets were achievable on either a sale-by-sale basis or as a collective target for the entire Block. Forage production and water yields did not appreciably differ between the analyses.

Only the old growth acres provided in Years 1 and 11 differed greatly between the analyses. More old growth acres could be generated on a Block-wide basis, while achieving timber harvest targets, than could be generated by the individual sale analysis. In Year 1, the Block-wide analysis provided 28 more acres of old growth than did the individual sale analysis, and in Year 11 the difference was 128 acres, a 23% increase over the that generated by the individual sale analysis. But in neither year could either analysis achieve the Forest Plan standard and guideline of 5% of the area, 795 acres, of old growth. The Block-wide analysis provided 3.5% and 4.2% of the Block acres in old growth conditions in Years 1 and 11, respectively. In Year 11, the 795 acre minimum old growth constraint cannot be achieved, regardless of Year 1 harvest levels. In Years 31 and 41, the old growth acres generated by the individual sales analysis exceeded that generated in the total Block analysis. This result is a function of harvesting in Year 31. Due to greater flexibility in selecting stands for harvest over time in the Block analysis, more timber is available and then harvested in Year 31 than in the individual sale analysis (table 3). As a result, fewer acres in the Block analysis qualify for old growth status in Years 31 and 41.

Although differences are not dramatic, these results are consistent with a commonly held hypothesis that applying Forest Plan standards and guidelines to large planning areas is less restrictive than applications to small areas. However, the relatively minor effects reported here are not really surprising given the questions

Old Growth Acres by Planning Unit

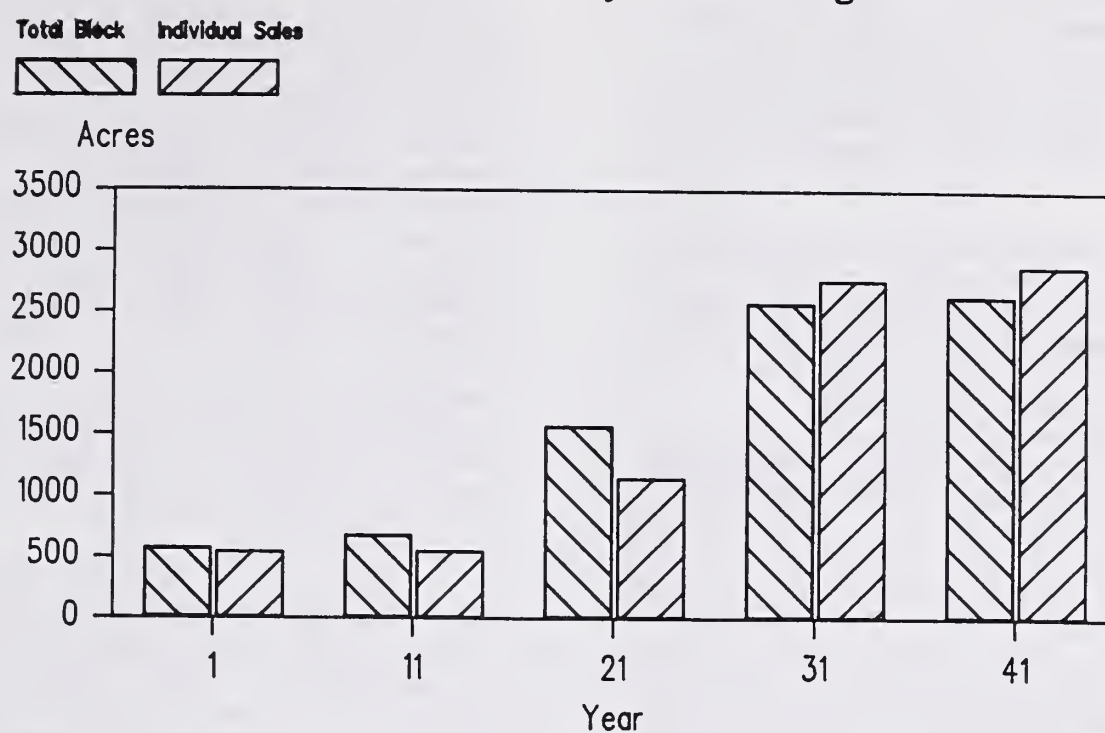


Figure 2: Old growth acres comparisons over time as a function of planning unit

Incremental Water Yield by Planning Unit

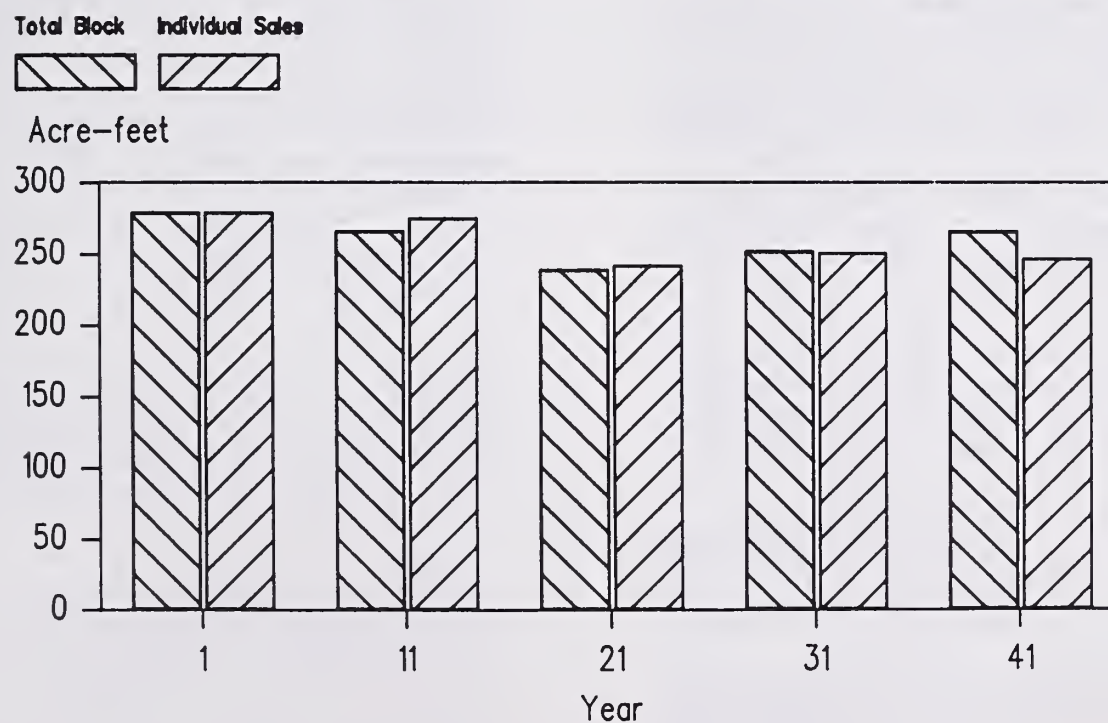


Figure 3: Incremental water yield comparisons over time as a function of planning unit

asked and the characteristics of the area studied, and they reflect three important and interrelated aspects of the planning process: the planning unit level used to generate targets, the basis for allocating resource targets, and the effect of the homogeneity of the area on the provision of a target resource.

The timber targets were generated based on current stand volumes, aggregated to the timber sale and 10-K Block levels. Therefore, little difficulty existed in obtaining the harvest volume targets either by individual sale or when allocated in aggregate to the entire Block, since the targets were built from below based on resource capabilities.

On the other hand, the provision of old growth acres did vary as a function of planning unit size. Old growth targets were generated based on Forest Plan standards and guidelines for all ponderosa pine areas on the forest with slopes less than 40%. This target was generated from above, and disaggregated to lower planning units. Thus as planning unit size decreases, from the forest, to the Block to the individual sale, old growth targets become increasingly difficult to meet.

The basis on which targets are allocated also influences the capability of a system to provide other resource outputs. Take, for example, the case of an individual timber sale, a unit of land defined primarily on the basis of providing one particular output, timber. Such an area will be unlikely to produce other resources in proportion to its ability to produce timber unless these other resources are highly and positively correlated to standing volume.

Last, as the homogeneity of the area analyzed increases, aggregating and disaggregating target resource outputs becomes easier. Only for the Bar M Sale is there a statistical difference between the mean volumes per acre for each timber sale and for the Bar M Block as a whole, and no statistical differences exist between the variances of the volume per acre for each individual sale and that for the overall Block variance (table 4). In terms of timber volumes, each sale represents a microcosm of the overall Block, and thus allocating timber targets to an individual sale was easy to achieve.

This analysis provides three lessons for those interested in forest planning. First, the ability of an area to provide resource outputs depends on the level from which targets are generated. If generated from below, the difficulties in achieving aggregate targets are minimized when these overall targets are subsequently disaggregated. For example, overall Forest-level timber harvest levels can be achieved if these harvest levels were built based on the aggregation of the capabilities of planning units that reflect actual resource capabilities. But for other resource targets not based on aggregation, such as old growth in this example, such disaggregation is not as easy because the targets do not reflect resource capabilities.

Second, the basis for allocating targets to particular units of land will impact resource outputs. Although volume may be, and probably is, an appropriate basis for allocating timber harvest, it is not necessarily the appropriate basis for allocating other resource targets, such as old growth acres or wildlife habitat.

Third, the more homogeneous an area with respect to a particular resource, the easier it is to disaggregate the output target for that resource. Under conditions where small planning units represent in microcosm the larger planning unit, the task of disaggregation to achieve desired output levels is greatly simplified. If, for example, every acre of a forest had identical timber characteristics, achieving harvest volume targets would be relatively easy indeed. But the complexity and difficulty of achieving output targets increases as management unit heterogeneity increases.

No easy answer exists for dealing with the problems identified above. However, the use of a DSS such as TEAMS allows for the rapid analysis of relatively large and complex allocation problems and can identify optimal solutions to these problems which satisfy management constraints. Such systems can be used to both generate potential resource outputs from below and to "best" allocate targets generated from above. As the Forest Plan implementation process continues, the number of such allocation problems will increase. Planning to achieve answers to these problems will require more sophistication than the Mylar map overlay and hard copy single-resource inventory data techniques that foresters

have used in the past. An alternative to such an approach would be

"...A stand based data base interacting with the simulation model [that] could provide a quick evaluation of alternate spatial allocations using the most current stand conditions. If such a system is further integrated into an operating GIS, map work would be extensively reduced and intuitive problem solving would be facilitated" (Keller 1986, p. 129).

This is in essence the definition of a decision support system. Decision support systems such as TEAMS can greatly aid in the analysis of these complex planning problems to generate technically feasible solutions. Such solutions can then provide information useful for the essentially political task of deciding how "best" to manage the National Forests.

LITERATURE CITED

Allen, T.F.H. and T.B. Starr. 1982. Hierarchy: Perspectives for Ecological Complexity. University of Chicago Press. Chicago, IL. 310p.

Allen, T.F.H., R.V. O'Neill, and T.W. Hoekstra. 1984. Interlevel relations in ecological research and management: some working principles from hierarchy theory. USDA Forest Service, Gen. Tech. Rpt. RM-110. Rocky Mtn. For. and Range Expt. Sta. Ft. Collins, CO. 10p.

Armel, Bryan N. 1986. "Area analysis and version II of FORPLAN." p. 143-152 in Bailey, R.G. (ed.). Proceedings of the workshop on lessons from using FORPLAN. April 29-May 1, 1986. Denver, CO. Washington, D.C., U.S. Dept. of Agric. Forest Service, Land Management Planning Section. 286p.

Cortner, H.J. and D.L. Sweitzer. 1983. "Limits to the hierarchical planning and budgeting systems: the case of public forestry." Journal of Environmental Management 17: 191-205.

Covington, W.W., D.B. Wood, D.L. Young, D.P. Dykstra, and L.D. Garrett. 1988. TEAMS: A decision support system for multiresource management. Journal of Forestry. 86(8):25-33.

Davis, Lawrence S. and K. Norman Johnson. 1987. Forest Management. Third Edition. McGraw Hill Book Company. New York, NY. 790p.

Dykstra, Dennis P. 1987. "Evaluation of FORPLAN from an operations research perspective: discussant's comments." p. 145-146 in Hoekstra, Thomas W., A.A. Dyer, and Dennis C. LeMaster, (technical editors). FORPLAN: An evaluation of a forest planning tool. USDA Forest Service, Gen. Tech. Rpt. RM-140. Rocky Mtn. For. and Range Expt. Sta. Ft. Collins, CO. 164p.

Fox, Bruce, MaryAnne Keller, Andrew J. Schlosberg, and James E. Vlahovich. 1989. Opportunity costs of implementing forest plans. Environmental Management. 13(1):75-84.

Hrubec, Robert J. 1976. National forest system working circles: a question of size and ownership of composition. USDA Forest Service, Gen. Tech. Rpt. PSW-16. Pacific Southwest For. and Range Expt. Sta., Berkeley, CA. 8p.

Keller, Daniel P. 1986. "Spatial allocation of FORPLAN solutions." p. 122-129 in Bailey, R.G. (ed.). Proceedings of the workshop on lessons from using FORPLAN. April 29-May 1, 1986. Denver, CO. Washington, D.C., U.S. Dept. of Agric. Forest Service, Land Management Planning Section. 286p.

Merzenich, James P. 1986. "Integrating information flows in forest planning: disaggregation and interpretation of FORPLAN, version 1, solution." p. 250-255 in Bailey, R.G. (ed.). Proceedings of the workshop on lessons from using FORPLAN. April 29-May 1, 1986. Denver, CO. Washington, D.C., U.S. Dept. of Agric. Forest Service, Land Management Planning Section. 286p.

Milne, Bruce T. 1987. "Hierarchical landscape structure and the forest planning model: discussant's comment." p. 128-132 in Hoekstra, Thomas W., A.A. Dyer, and Dennis C. LeMaster, (technical editors). FORPLAN: An evaluation of a forest planning tool. USDA Forest Service, Gen. Tech. Rpt. RM-140. Rocky Mtn. For. and Range Expt. Sta. Ft. Collins, CO. 164p.

Montgomery, Douglas C. 1984. Design and Analysis of Experiments. Second Edition. John Wiley and Sons. New York. 538p.

Naveh, Z. and A.S. Lieberman. 1984. Landscape Ecology Theory and Applications. Springer-Verlag. New York. 356p.

Ryberg, Stephen M. and Brad Gilbert. 1986. "Use of version II FORPLAN in project analysis." p. 130-142 in Bailey, R.G. (ed.). Proceedings of the workshop on lessons from using FORPLAN. April 29-May 1, 1986. Denver, CO. Washington, D.C., U.S. Dept. of Agric. Forest Service, Land Management Planning Section. 286p.

Schugart, H.H. and Bradley J. Gilbert. 1987. "An ecological evaluation of FORPLAN in national forest planning." p. 105-121 in Hoekstra, Thomas W., A.A. Dyer, and Dennis C. LeMaster, (technical editors). FORPLAN: An evaluation of a forest planning tool. USDA Forest Service, Gen. Tech. Rpt. RM-140. Rocky Mtn. For. and Range Expt. Sta. Ft. Collins, CO. 164p.

Conflict Resolution in Multiresource Forest Management via Multiobjective Analysis¹

Aregai Tecle, W. Wallace Covington, D. Brent Wood, and Bruce E. Fox²

Abstract.--This paper develops and presents a methodology for conflict resolution in forest resources management. In the process, sources and possible types of conflicts are identified and some conflict analysis methods revised. Then, a ponderosa pine forest resources management problem with multiple conflicting objectives is solved using a cooperative game theoretical procedure. This leads to the determination of the most satisfying ponderosa pine forest treatment level under the conditions considered for analysis in this study. The treatment level which provides the vector of best objective function values is thinning the forest to a basal area of 48 to 60 ft²/acre.

INTRODUCTION

Federal regulations and Forest Service guidelines require that national forests be managed for joint optimization of the different commodity resources (such as timber, herbage, water and minerals), amenity resources (such as wildlife, fish, visual quality and cultural values) and their supporting environment like soil, land and facilities. Even though all of these components are interrelated as parts of an interacting system, many of their interactions are competitive so that any management attempt for joint optimization, in the true meaning of the word, of all the resources in a forest system practically impossible.

Conflicts in forest resources management are further intensified by the presence of a variety of individuals and/or groups with conflicting interests

and demands on the resources. This is particularly so in the ponderosa pine forests of the Southwest where there is not any particular dominant use, but rather the forest supports increasingly heavy demands by various user groups on both its commodity and amenity resources. Because of this situation, conflicts over forest resource use are common and seriously impact multiresource management. The conflict situation is further exacerbated by the lack of appropriate techniques for resolving such conflicts.

The nature of conflicts in forest resource management and the methods for dealing with the problem are discussed in this paper. First, the possible types of conflicts that can occur in the management of the resources in the southwestern ponderosa pine forest ecosystem are identified and described. Then, after a brief introductory review of the general conflict analysis procedure, a detailed description of the conflict resolution methodology used in this study is presented. This particular technique is the Nash-Harsanyi method (Goicoechea and others 1982) which uses a cooperative game theoretical concept to arrive at a compromise solution to a problem with several conflicting objectives. As an example of the latter, a ponderosa pine forest resource management problem with several objectives, some of which are

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²Aregai Tecle is Assistant Professor, W. Wallace Covington and D. Brent Wood are Professors and Bruce E. Fox is Assistant Professor, School of Forestry, Northern Arizona University, Flagstaff, Arizona 86011.

conflicting, is formulated and solved. Once the problem is solved, the results are analyzed.

CONFLICTS IN FOREST RESOURCE MANAGEMENT

Forest resource management issues, concerns, and opportunities are characterized by a multiplicity of objectives, criteria, decision-makers, and constituents all impinging upon ecosystems. This makes the management of forest resources a complicated problem which requires decision making not only under several non-commensurable and conflicting objectives, but also in the presence of various groups of decision-makers and user constituents with conflicting interests in the different forest resource elements. Non-commensurability relates to the multiplicity of ways in which natural resources problems can be viewed or expressed simultaneously. Resources can be analyzed in terms of their economic benefits, aesthetic values, physical and biological components, and the social, cultural, political, and institutional conditions imposed upon their utilization.

Conflicts manifest of the existence of individuals or groups having different interests, goals, or objectives for a project, property or idea. Conflicts among interest groups or decision makers may be of varying intensity and complexity. Some may represent minor differences in the decision makers' points of view about an issue or ways of accomplishing a task, or they may strain the relationship among countries significantly (Fraser and Hipel 1984). Although conflicts may be as silent as citizen dissatisfaction about an issue, which is usually expressed indirectly through ballots or election returns, they may also be intense and even explosive. The latter type is usually manifested in court litigations, picket lines, street demonstrations, or even armed fighting.

Conflicts arise when a number of objectives cannot be optimized simultaneously. This occurs when the objectives are competitive, that is, when improvement in one objective is associated with deterioration in another. Psychologically, such a conflict is considered to occur when two or more motives are partially blocking each other (Zeleny 1982). According to this definition, the prime cause for conflict lies in the cognitive domain, in cognitive differences in perception or interpretation of the components of a

given decision situation. As such, conflict becomes cognitive conflict generated by poor communication, misunderstanding, and positional inflexibility among parties. Socially and economically, conflict may also be defined as the interference by one or more individuals or groups on the attempt by others to achieve their social, and economic desires, or goals. These desires may be related to social equality, economic opportunity, or cultural, religious, or political freedom.

Conflicts in forest resources management may be caused by similar situations. Conflicting objectives in forest resources management may reflect different interests of a single decision-maker. A conflict of this nature, for example, may arise when a forest manager is confronted with the problem of attempting to maximize timber production while at the same time minimizing environmental degradation of the forest system. These two objectives are usually incompatible with each other and need some kind of tradeoff analysis. But in most cases, conflicting objectives represent conflicting desires of different decision makers or parties. Such conflicts are commonly encountered among parties because one party wants to get a larger share of some resource, such as timber, which comes at the expense of the other parties desiring the same resource. This kind of conflict is prevalent in the southwestern ponderosa pine forest areas among water users such as the Salt River Project on one hand and either Native American groups or other valley water users on the other. Such conflicts are also found among different timber companies who obtain their supply from the same forest areas.

There are also conflicts among groups who want different things from a forest system. Environmental groups and timber harvesters, for example, would like to see forests managed to satisfy their own specific desires. Another example of intergroup conflict in the area is between forest land developers, and traditional Native Americans who would like to maintain the sanctity of a particular area in the forest.

The forest resource management problem to be analyzed in this study is applicable to either conflict situations among different decision makers, or the single decision maker's dilemma when confronted with a number of conflicting objectives.

METHODS OF CONFLICT MANAGEMENT

Generally speaking, many conflict management schemes are known to have been used, some successfully and some not, to settle conflict situations that arise in the process of decision making. In this section a brief overview of conflict management methods is provided first, then followed by a detailed description of the particular technique used to evaluate the multiobjective problem under consideration.

An Overview of Conflict Management

People have tried many different ways of settling conflicts. Zeleny (1982) presents a repertoire of some common methods of conflict management including neglect, denial, containment, control, solution, resolution, and dissolution a brief discussion of which is provided herewith. Neglecting and denying a conflict situation are two different things. Neglecting a conflict means ignoring it or doing nothing about it, that is, letting it run its course without any interference. Denying implies refusing to accept the conflict's existence or reality such as by belittling major differences in decision making among different interest groups in forest resources management to make the situation look like a conflict-free environment. Such conflict denial usually involves the use of persuasion methods such as propaganda, brainwashing, or lying. In short, neither conflict neglect nor conflict denial lead to any positive steps in settling a dispute.

Conflict containment and control, on the other hand, can be helpful methods if applied properly. Conflict containment means temporarily freezing a conflict from progress to gain time for thinking and rationalization, while controlling a conflict involves allowing a conflict to progress within a certain limitation in accordance to prescribed rules. A conflict between wildlife managers and timber producers, for example, may be controlled by allowing loggers to cut trees as long as the cutting is done appropriately to leave adequate tree density for shelter in some areas, while cutting trees in others, to enhance forest browse production.

Conflict solution, resolution, and dissolution are more effective methods of settling conflicts. Solving a

conflict is characterized by a single decision maker in a single objective environment or in an environment with multiple but complementary objectives, where optimizing the single objective or the complementary objectives is the sole criterion for action. Conflict resolution, on the other hand, involves consideration of multiple objectives some of which are in competition. It accepts the conditions which create the conflict, and seeks a compromise settlement, or consensus among the different decision makers involved. The process of resolving a conflict requires each party to give up something he or she originally desired in order to arrive at an equitable outcome or share for all parties concerned. Negotiation, mediation, arbitration, and bargaining are common tools used in conflict resolution. Conflict resolution, however, does not usually affect the conditions which produced the conflict situation, rather it results only in reducing the intensity of the conflict situation. Conflict elimination requires innovation, or inventing a new prominent alternative action that can result in a conflict-free situation. This is conflict dissolution. Since conflict dissolution is difficult to accomplish, however, most attempts of conflict management are usually geared toward resolving a conflict.

Mathematical techniques have been developed that can help resolve problems with conflicting objectives. Single objective problems can be handled using any classical optimization technique or mathematical programming procedures. To arrive at conflict resolution or dissolution, however, any one of a number of multiobjective programming techniques can be used (Zeleny 1982, Kok 1986). The techniques most commonly used in conflict analysis are usually based on the game theoretical concept. One such method is the so called conflict analysis of Fraser and Hipel (1984, 1989).

Conflict analysis is a reformulation and extension of metagame analysis (Howard 1971) which has some linkage with classical game theory (Von Neumann and Morgenstern 1953). The technique assumes no cooperation among participants when analyzing a problem with multiple conflicting objectives. This is in contrast to the cooperative game procedure being used to analyze the example problem in this paper. Another game theoretical procedure that can be applied to analyze conflicts in forest resource management is hypergame.

Hypergame is useful in a situation where one or more of the parties or participants have some misunderstanding about the true nature of the conflict situation (Fraser and Hipel 1984). This is usually the case when negotiating a sales contract. The buyer usually conceals the amount he or she is willing to pay in order to get the lowest possible deal. Information may also be hidden during negotiation by parties having conflicting interests in resource utilization with the intention of each side getting a better concession from the other.

Cooperative Game

In this paper, a cooperative game theoretical concept, known as the Nash cooperative game solution concept (1950, 1953) is employed as in Tecle and Duckstein (1989) to arrive at a compromise solution to the multiobjective ponderosa pine forest resources management problem under consideration. Game theory, in general, is a mathematical study of conflict resolution and may be classified as cooperative or non-cooperative game. In a cooperative game (CG), the participants have the opportunity to communicate with one another and form binding and enforceable agreements among themselves. Such an agreement results in the formulation of a payoff matrix as discussed in the next section.

A number of solution schemes have been proposed to J-person cooperative game problems (Rapoport 1970, Guiasu and others 1980). In most cases, the solution concepts are usually based on the subjective choice of weights, bounds and/or distances. The solution concept in this paper is, however, based on a certain set of axioms and the subjectivity of the decision maker (DM) in accepting or rejecting the axioms and determining the "status quo" point. The status quo point in a cooperative game is the vector of payoffs which all players can be sure of obtaining if they do not cooperate, and each tries to optimize his or her individual objectives. To state it quantitatively, let the payoff space be denoted by P and the elements in P by $f(j,k)$, for $j = 1, 2, \dots, J$ and $k = 1, 2, \dots, K$, then the status quo point is a disagreement vector, $f^{**} \in P$ such that $f^{**} = \{f_1^{**}, f_2^{**}, \dots, f_J^{**}\}$, and also $f(j,k) \geq f_j^{**}$ in which $f(j,k) > f_j^{**}$ for at least one value of j (Rapoport, 1970).

Based on this assumption, Nash (1950, 1953) developed a solution procedure for two-player bargaining games. Harsanyi (1977) extended the Nash procedure to a J-players cooperative game ($J \geq 3$) to obtain a unique bargaining solution. The Nash-Harsanyi solution, f^* in which $f^* = \{f_1^*, f_2^*, \dots, f_J^*\}$ can be obtained using the following equation:

$$f^* = \max[S_k = \pi \sum_{j=1}^J (f(j,k) - f_j^{**})] \quad (1)$$

subject to $f(j,k) \geq f_j^{**}$, and $f(j,k) \in P$; and f^{**} is as described above, while S_k is a vector valued achievement level of the objectives under a particular k ($k = 1, 2, \dots, K$) treatment level.

This equation can be derived in one of two ways. It can be obtained using Zeuthen's bargaining principle (Zeuthen 1930) which states that the next concession always comes from the objective having the least risk in a conflict. It can also be derived from satisfying Nash's axioms which can be described as follows:

1. Feasibility. The payoff space, P , of the cooperative game is always closed, bounded, and convex, and that there exists at least one $f(j,k) \in P$ such that $f(j,k) > f_j^{**}$ as stated above.
2. Collective rationality. If $f^* = (f_1^*, f_2^*, \dots, f_J^*)$ is a solution, there is not any other point in the payoff space, P , which yields every player a payoff higher than f^* .
3. Joint efficiency. Players joining in a coalition can get jointly more than the sum of what they can get if they play every man for himself against a coalition of all others. That is, the efficiency is synergistic. If f^* is nondominated in P , there is not any other vector $h \in P$, $h \neq f^*$ such that $h \geq f^*$.
4. Symmetry. If the game is symmetric, every player gets the same payoff.
5. Linear invariance. If two versions of the same bargaining game differ only in the units and origins of the utility function, then the respective solutions are related by the same utility transformation.
6. Independence of irrelevant alternatives. If the payoff space of the multiobjective problem is expanded, while the status quo

point remains the same, then the new solution must either be in the added space or remain in the original space. Likewise, if a payoff space which does not contain the solution is deleted while the status quo point remains the same, then the solution would also remain the same.

The idea is that if the players agree to accept the axioms as general principles then they can apply a bargaining procedure that satisfies the axioms in all situations in order to get a satisfying solution. This procedure and Zeuthen's bargaining procedure arrive at the same solution (Harsanyi 1977) which can be obtained using the above Nash-Harsanyi model (Szidarovszky and others 1984). In this study, the Nash cooperative game procedure is used to analyze a forest resource management problem with conflicting objectives.

FOREST RESOURCES MANAGEMENT CASE EXAMPLE

To illustrate the application of conflict analysis to multiresource management, a simplified problem using data from the ponderosa pine forests of the Beaver Creek Watershed is analyzed. The Beaver Creek Watershed is located about 30 miles south of Flagstaff, Arizona, in the Coconino National Forest. This watershed was used as a study area for a 22 year experimental pilot project to demonstrate multipurpose forest resource management. During that period different parts of the watershed were subjected to varying vegetation treatment levels to determine the effects of such treatments on the forest resources and conditions in the area. Descriptions of the different vegetation treatments performed can be found in USDA Forest Service (1977), Brown and others (1974), Ffolliott and Thorud (1975), Baker (1982, 1986) and Tecle and others (1988). Data on the effect of treatment levels on water runoff, sediment yield, flood magnitude, wildlife, range forage, recreational use, and scenic beauty have been collected, and analyzed to produce resource response functions showing how vegetation modification practices affect these outputs (Brown 1976, Baker and Rogers 1983, Hibbert 1983, Mitchell and Joyce 1986).

In this paper, a systems approach to a complex resources management problem in which compromises are made among conflicting objectives is described. The complexity of multiresource management stems from the interaction of a hierarchy of complex

and dynamic systems including a landscape of ecological systems and national, regional, and local social and political systems.

A conceptual framework for analyzing multiresource management problems can be derived from a set model proposed by Rolfe Leary (1985) in his 1985 book, Interaction Theory in Forest Ecology and Management. Taking a few liberties with Leary's set model, multiresource management can be viewed as the interaction of sets of resources (both biotic and abiotic), users (both human and other biotic users), specific locations, time, natural disturbances, and management. Symbolically this can be expressed as:

$$\text{MRM} = R_a \times R_b \times U_b \times U_h \times L \times T \times D \times M \times \text{SP} \quad (2)$$

where:

MRM = multiresource management

R_a = abiotic resources (water, soil, nutrients, salt licks, etc.)

R_b = biotic resources (trees, shrubs, grasses, forbs, animals, microbes, etc.)

U_b = biotic users of populations (all biota except humans)

U_h = human users of populations (as biota with technology for extensive impacts)

L = geographic locations (stands, management units, watersheds, districts, national forests, states, etc.)

T = time (time steps from hourly through centuries)

D = disturbances (fire, drought, insect outbreak, etc.)

M = management activities (burning, fencing, thinning, harvesting, fertilization, road building, recreation site development, etc.)

SP = sociopolitical factors (local, regional, and national)

This model leads those concerned with multiresource management to think more clearly and more comprehensively when analyzing alternative management strategies.

To illustrate this approach we consider a multiresource management analysis where parties are concerned with the abiotic resource of water, the biotic resource of herbage, the biotic resource of deer, the biotic resource of livestock, the human users of water, the human users of recreation, the human users of timber, a single location, a time span of 5-10 years since the initial treatment, the management activities of harvesting and thinning,

and the overall treatment cost. In this paper, the procedure was demonstrated by analyzing data gathered from different parts of a particular forest watershed, the Beaver Creek Watershed. And even though the data was obtained from a number of subwatersheds each subjected to a different vegetation treatment level, the subwatersheds were considered spatially homogenous to simplify the problem for analysis. Further simplification was also made by not including other disturbances, sociopolitical factors, and information from locations outside the study site.

To analyze the problem, five general objectives, eight resource criteria (table 1), and eight response functions (fig. 1), one for each criterion were developed (Teclé 1988) in accordance with USDA Forest Service's multipurpose forest resources management guidelines (USDA Forest Service 1982). The response functions are constructed for joint analysis in a multiobjective framework (Teclé 1987, Teclé and others 1988). The desire is to enable obtaining the best possible combination of outputs from the forest system while at the same time accounting for environmental impacts of the particular management activity, and also resolving conflicts among different interest

groups having a stake in the way the resources are managed.

The eight resource response functions have been used as objective functions to express the interests and aspirations of different forest resources managers and other interest groups. The objectives are:

- (1) Maximizing water yield
- (2) Minimizing sediment loss
- (3) Minimizing flood magnitude
- (4) Improving deer habitat
- (5) Maximizing aesthetic values
- (6) Maximizing forage production
- (7) Maximizing timber production, and
- (8) Minimizing total cost

For simplicity, a regression analysis of the data was conducted leading to eight polynomial functions described in the following general form. The equation is a function of a single independent variable, percent basal area removed.

$$f_j(x) = \sum_i a_i x^i, \quad j = 1, 2, \dots, J \quad (3)$$

where

$f_j(x)$ = value of objective function j ,
 $(j = 1, \dots, J)$
 J = the number of objective functions, which is 8

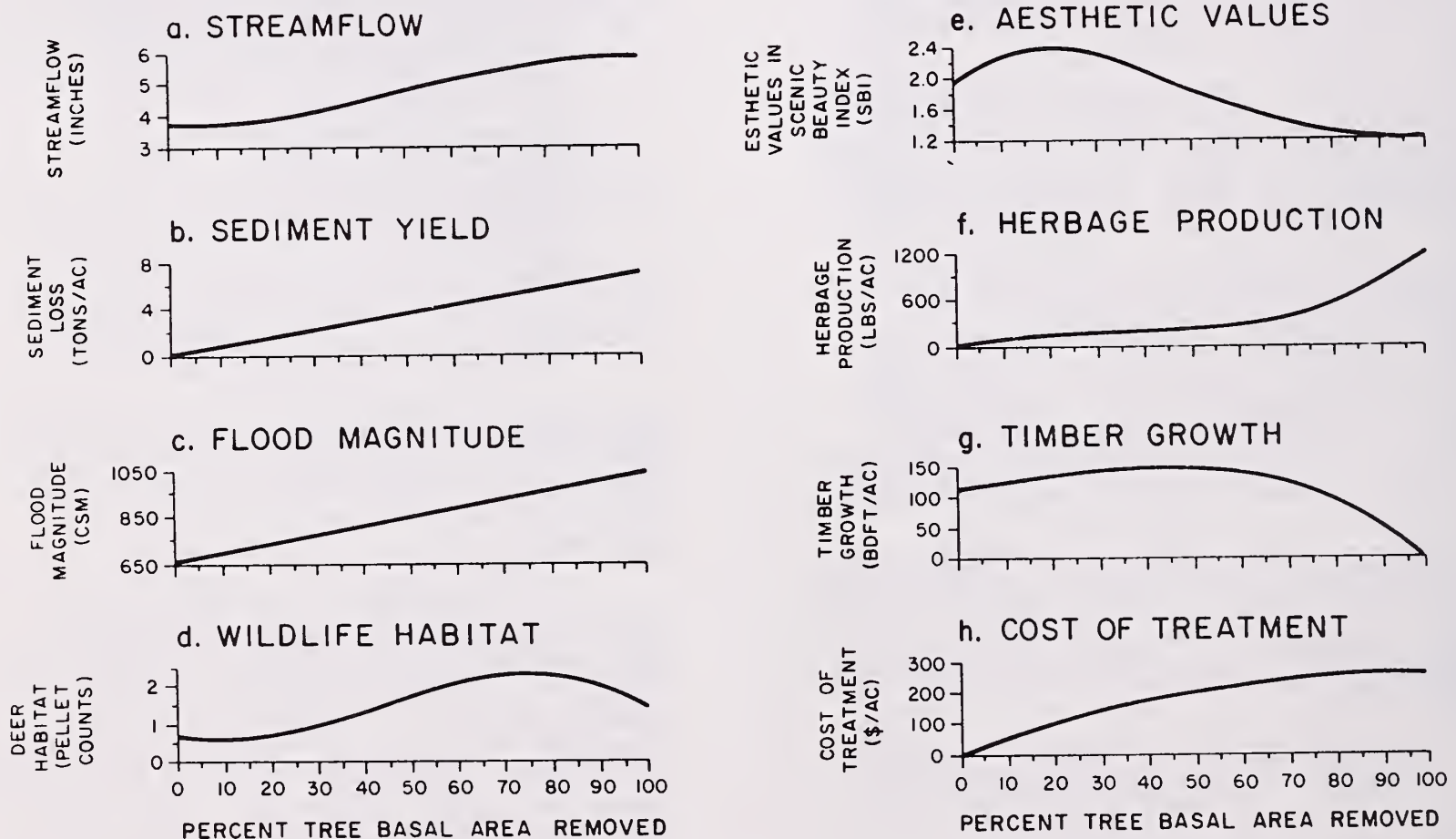


Figure 1. Effect of vegetation management on different forest resources.

$i = 0, 1, 2, \dots$ is the exponent of x
 a_i = coefficient of x^i , and
 x = percent basal area removed from the ponderosa pine forest in the Beaver Creek Watershed.

Determination of percent basal area removal is based on an average tree basal area of 120 ft² per acre for untreated ponderosa pine forest on Siesta-Sponseller soils in the Beaver Creek Watershed as reported in, for example, Brown and others (1974), Baker (1975) and Brown (1981). Under this condition, a watershed having 50% of its tree basal area removed is considered to be equivalent to one having 60 ft²/acre tree basal area. Tree basal area is the area in square feet occupied by living trees on one acre of land (Forbes and Meyer 1961, Brown 1981). Basal area is determined by measuring the cross section of the trunk of sample trees at a point 4.5 feet above ground. Since the trees in the watersheds are not distributed uniformly, the average basal area on the study site was used to construct the resource response functions. These functions are presented graphically in Figure 1. The individual graphs in the figure are the response function curves for the 8 different resource elements under consideration.

Information for developing the resources response functions was obtained from previously collected data on the Beaver Creek experimental watershed. The annual averages for a five-year data set for different vegetation treatment levels have been used in combination with supplemental information from various published materials such as those in Brown and others (1974), Baker and Brown (1974), Ffolliott and Thorud (1974, 1975), Baker (1982, 1986), Brown (1982), and Ffolliott and others (1989).

APPLICATION AND ANALYSIS OF RESULTS

In order to apply the Nash solution concept of cooperative game approach to the multiobjective forest resource management problem, discrete values of the eight objective functions for each one of 15 vegetation treatment levels were obtained. The 15 treatment levels consisting of A1, A2, A3, A4, A5, A6, A7, A8, A9, A10, A11, A12, A13, A14, and A15, respectively represent 0, 15, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 85, and 100 per cent tree basal area removal. These are assumed to be feasible alternatives from which the most satisfying treatment level can be selected. The values of the resource

Table 1. Objectives, specifications, criteria and criterion measures of the ponderosa pine forest resources management problem.

Objectives	Specifications	Criteria	criterion measures
Increase water yield	water quantity, streamflow, water quality, sediment yield, flood hazard	streamflow sediment yield flood level	Net change (inches) Tons per acre cubic feet/sec/mi ²
Develop recreation	recreation use (camping, hiking, hunting, fishing, horse riding, nongame use, sight seeing, picnicking, fauna-flora structure and others)	deer population density aesthetic value	pellet group count scenic beauty index
Improve range condition	livestock and wildlife forage	herbage production	pounds per acre
Timber production	timber stand improvement (both quality saw timber, and quantity), fire wood and fence post	timber growth	board feet per acre
Minimize total cost	O and M cost* capital and indirect cost	total cost	dollars per acre

*O = operation, and M = maintenance

response functions in figure 1 corresponding to these treatment levels were obtained and constructed to form the evaluation matrix of table 2. Then the Nash-Harsanyi solution procedure specified in the previous section is utilized to select the compromise treatment level.

In applying the Nash-Harsanyi model to the evaluation matrix of table 2, the geometric distances from the status quo point of the 15 points, each point representing a vector of criterion function values, S_k under alternative treatment level k ($k = 1, 2, \dots, 15$) were determined. This was done, by first choosing from $f(j,k)$, the minimum value for each criterion j as the status quo point. The criterion values in column 2 of table 4 constitute the status quo point for the problem considered. Then using equation [1], the geometric distance of point S_6 (which is the compromise point) was determined as follows:

$$\begin{aligned} & [(4.49-3.68)*(-3.2+7.56)*(-818 \\ & +1040.1)*(2.1-1.15)*(1.41-0.53)* \\ & (204-0.66)*(147.5-0.32) \\ & *(-168+259.1)] = 0.1788E+10 \end{aligned} \quad (4)$$

Such computation was made 15 times, one for each alternative treatment level. And maximizing the 15 distances provides the unique compromise solution, S_6 . Thus, alternative A6 representing 40% (48 ft²/acre) basal area cut, with a residual basal area of 72 ft²/acre is found to be the compromise solution to the problem under consideration. Figuratively, this solution represents a saddle point (in a 2-dimensional sense) in the feasible payoff space.

To demonstrate the solution procedure in a 2-dimensional graph, the wildlife habitat (in deer pellet counts) and aesthetics (in scenic beauty index) response functions are drawn in figure 2. The individual optimum values of these response functions are 2.38 (in scenic beauty index) at 20% cut for aesthetics, and 2.38 (in pellet counts) at 75% cut for deer. These values which are shown, respectively, as points a and

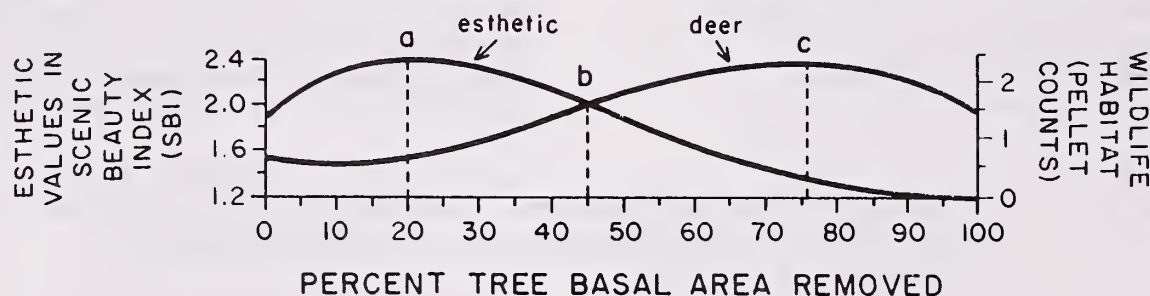


Figure 2. Graphical representation of a compromise solution for a problem with two competitive objectives.

Table 2. Evaluation matrix: criterion function values versus alternatives

Criteria	Alternative treatments as percent tree basal area cut														
	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15
Streamflow (inches)	3.78	3.85	4.05	4.18	4.33	4.49	4.66	4.84	5.02	5.19	5.36	5.51	5.65	5.86	5.95
Sed. yield (tons/ac)	-0.12	-1.36	-2.12	-2.49	-2.85	-3.20	-3.55	-3.89	-4.24	-4.58	-4.92	-5.26	-5.61	-6.32	-7.46
Flood lev. (CSM)	-655.	-717.	-758.	-778.	-798.	-818.	-838.	-858.	-877.	-897.	-916.	-934.	-953.	-989.	-1040.
Aesthetic (index)	1.91	2.36	2.36	2.30	2.21	2.10	1.99	1.86	1.74	1.63	1.52	1.43	1.36	1.26	1.25
deer pellet (counts)	0.67	0.63	0.86	1.03	1.21	1.41	1.61	1.81	1.99	2.15	2.27	2.35	2.38	2.24	1.43
Herbage production (lbs/ac)	0.76	128.	168.	183.	194.	204.	213.	223.	237.	259.	291.	337.	401.	606.	1185.
Timber growth (bdft/ac)	116.	130.	139.	143.	146.	147.5	148.	147.	144.	140.	133.	123.	111.	77.	.42
Total cost (\$/acre)	-4.71	-76.6	-117.	-135.	-152.	-168.	-182.	-196.	-208.	-219.	-229.	-237.	-245.	-255.	-259.

c in figure 2, cannot be achieved simultaneously. They are competitive. Thus, the compromise treatment level which would yield the best value for each objective such that any improvement in either objective values would be impossible without adversely affecting the other is 45% basal area cut. This cut would give the compromise solution at point b (fig. 2) with the values of 1.61 for wildlife and 1.99 for aesthetics. Furthermore, if in addition to specifying the status quo point, other constraints are also introduced to represent a maximum acceptability of foregone benefits or costs, then the solution would be different. For example, if it were determined that the threshold value for wildlife survival was a minimum value of 2 deer pellet counts, then the preferred treatment would be 55% cut which would yield a compromise solution of 2 for wildlife, and about 1.7 for aesthetics (fig. 2).

Using the computed geometric distances as criteria, a preference ranking of the different alternative treatment schemes was made as shown in table 3. In order of preference, A6, 40% tree basal area removal followed by A7, the alternative with 45% removal are the best alternative management schemes for the problem under consideration. The worst is A15, the 100% tree basal area removal alternative. The other treatment levels occupy intermediate rankings as shown in table 3. The values of the criterion functions corresponding to each alternative vegetation treatment level are found in table 2 under the columns representing each specific treatment level.

The vector of criterion function values for the selected alternative vegetation treatment level, A6, is compared to other vectors of criterion function values in table 4. Specifically, the criterion function values for the first choice alternative action, A6 (Column 3), the second choice, A7 (column 4), the worst criterion values, or status quo point (column 2), and the best possible criterion values that can be obtained for each function if each were optimized separately (column 5) are compared. This comparison clearly shows where the criterion function values under the preferred alternative treatment level lie in comparison with the highest and lowest criterion function values. Aesthetic value is close to the optimal value; however, others, such as sediment

Table 3. Ranking of alternative treatment schemes

Alternative scheme (1)	Relative distance (2)	Ranking (3)
A1	.8971E+05	14
A2	.1242E+09	11
A3	.7477E+09	7
A4	.1233E+10	5
A5	.1612E+10	3
A6	.1788E+10	1
A7	.1742E+10	2
A8	.1450E+10	4
A9	.1085E+10	6
A10	.7245E+09	8
A11	.4109E+09	9
A12	.2075E+09	10
A13	.8121E+08	12
A14	.4945E+07	13
A15	.2419E-01	15

yield, flood level, and wildlife conditions, lie midway between the two extremes, while streamflow, herbage production and total cost are closer to the minimum values. The level of timber yield is optimized under the selected compromise alternative management level, A6, the 40% tree basal area removal.

CONCLUSIONS

Conflicts can provide decision makers with a decision motivating tension, and a frustration and dissatisfaction with the status quo, as well as a desire for resolving the conflict situation. In this study, modeling possible conflicts among different forest resources managers and interest groups lead, first, to the formulation of a resources management problem with eight conflicting objectives. The objectives are considered to represent the interests and aspirations of the different resources managers and other interest groups. Then, a mathematical bargaining procedure which assumes existence of cooperation among the participants is used to analyze the problem. This procedure is the Nash-Harsanyi cooperative game procedure which results in a compromise solution.

In conclusion, cooperative game theoretical concept can be successfully used to arrive at a compromise solution to a multiresource management problem with non-commensurate, and conflicting

Table 4. Comparing criterion function values for the selected alternative treatment level with the vectors of worst and best criterion function values.

Criterion function (1)	Worst value (2)	value for 1st Choice (3)	value for 2nd choice (4)	Best values (5)
Streamflow (inches)	3.78	4.49	4.66	5.95
Sediment yield (tons/acre)	-7.56	-3.20	-3.55	-0.12
Flood level (CSM)	-1040.00	-818.00	-838.00	-655.00
Aesthetic index (index)	1.25	2.10	1.99	2.36
Deer pellet (counts)	0.63	1.41	1.61	2.38
Herbage production (lbs/acre)	0.76	204.00	213.00	1185.00
Timber growth (bdft/acre)	0.42	147.50	148.00	148.00
Total cost (\$/acre)	-259.00	-168.00	-182.00	-4.71

objectives. The requirement is that certain axioms which the solution must satisfy, such as Nash's axioms have to be accepted a priori. . Once the parties accept the axioms (or Zeunthen's bargaining principle), and choose the "status quo" point, the technique enables determination of a unique solution to the multiobjective forest resource management problem. The status quo point may be either the Nash equilibrium point, a minimum solution point (Harsanyi 1977), or the result of the subjective choice of the decision maker. In this paper, the status quo point is taken to be the Nash equilibrium point minus 0.1 to avoid multiplication by zero. The process results in selecting alternative A6, the vegetation treatment level with 40% tree basal area removed. However, as is true in all problem solving techniques, the simplifying assumptions considered, the analytical techniques employed, and the adequacy of data gathered determine the outcome. Different assumptions, extensive data base on resource mixes, resource response functions, and use of other techniques may result in a different compromise solution.

REFERENCE CITED

- Baker, Jr., M.B. 1975. Modeling management of ponderosa pine forest resources. Watershed Management Symposium, ASCE Irrigation and Drainage Division, Logan, Utah, August 11-13, pp. 478-493.
- Baker, Jr., M.B. 1982. Hydrologic regimes of forested areas in the Beaver Creek watersheds. USDA Forest Service General Technical Report RM-90, June, 8p.
- Baker, Jr., M.B. 1986. Effect of ponderosa pine treatments on water yield in Arizona. Water Resources Research, 21(1):67-73.
- Baker, Jr., M.B. and H.E. Brown. 1974. Multiple use evaluations on ponderosa pine forest land. 18th Annual Arizona Watershed symposium Proceedings, Sep. 25, Arizona Water Commission Report No. 6, Phoenix, AZ, pp. 18-25.
- Baker, Jr., M.B., and J.J. Rogers. 1983. Evaluation of water balance models on a mixed conifer watershed. Water Resources Research, 19(2):486-492.
- Brown, H.E., M.B. Baker, Jr., J.J. Rogers, W.P. Clary, J.L. Kovner, F.R. Larson, C.C. Avery, and R.E. Campbell. 1974. opportunities for increasing water yields and other multiple use values on ponderosa pine forest lands. USDA Forest Service Research Paper RM-129, December, 36p.
- Brown, T.C. 1976. Alternative analysis for multiple use management: A case study. USDA Forest Service Research Paper RM-176, October, 16p.

- Brown, T.C. 1981. Tradeoff analysis in local management planning. USDA Forest Service General Technical Report RM-82, January, 12p.
- Forbes, R.D., and A.B. Meyer (eds.). 1961. Forestry Handbook. The Ronald Press Company, New York, N.Y.
- Ffolliott, Peter F., Gerald J. Gottfried, and Malchus B. Baker, Jr. 1989. Water yield from forest snowpack management: Research findings in Arizona and New Mexico. Water Resources Research, 25(9): 1999-2008.
- Ffolliott, P.F., and D.B. Thorud. 1974. Vegetation management for increased water yield in Arizona. Agricultural Experimental Station Technical Bulletin 215, The University of Arizona, Tucson, AZ, 38p.
- Ffolliott, P.F., and D.B. Thorud. 1975. Water yield improvement by vegetation management: focus on Arizona. Available from National Technical Information Service, Springfield VA 22161.
- Fraser, Niall M., and Keith W. Hipel. 1984. Conflict Analysis: Models and resolutions. Elsevier Science publishing Co., Inc., New York, NY. 377p.
- Fraser, Niall M., and Keith W. Hipel. 1989. Decision making using conflict analysis methodology. OR/MS Today, (October 1989 issue), pp. 22-24.
- Goicoechea, A., D. Hansen, and L. Duckstein. 1982. Introduction to multiobjective analysis with engineering and business applications. Wiley, New York, NY. 519p.
- Guigas, S., and M. Malitza. 1980. Coalition and connection in games. Pergamon Press, New York, NY.
- Harsanyi, J.C. 1977. Rational behaviour and bargaining equilibrium in games and social situations. Cambridge University Press, London, U.K.
- Hibbert, A.R. 1983. Water yield improvement potential by vegetation management on western rangelands. Water Resources Bulletin, 19(3): 375-382.
- Howard, N. 1971. Paradoxes of Rationality. MIT Press, Cambridge, Mass.
- Kindler, J. 1988. On the multiobjective framework of environmentally sound and sustainable water resources management. Water Resources Development, 4(2):117-123.
- Kok, Matthijs. 1986. Conflict analysis via multiple objective programming, with experiences in energy planning. Druk: ICG Printing, Dordrecht. 145p.
- Leary, Rolfe A. 1985. interaction theory in forest ecology and management. Martinus Nijhoff/Dr W. Junk Publ., Boston, MA. 219p.
- Mitchell, J.E., and L.A. Joyce. 1986. Use of a generalized linear model to evaluate range forage production estimate. Environmental Management, 10(3):403-411.
- Nash, J.F. 1950. The bargaining problem. Econometrica, 18(2): 155-162.
- Nash, J.F. 1953. Two person cooperative games. Econometrica, 21:128-140.
- Rapoport, A. 1970. Conflict resolution in the light of game theory and beyond. In: The structure of conflict, P. Swingle, ed., Academic Press, New York, N.Y.
- Szidarovszky, Ferenc, Lucien Duckstein, and Istvan Bogardi. 1984. Multiobjective management of mining under water hazard. European Jour. of Oper. Res. 15:251-258.
- Tecle, Aregai. 1987. Multiobjective forest watershed management. Proceedings of the Seventh Annual AGU Front Range Branch "Hydrology Days", Colorado State University, Fort Collins, CO, April 21-23, pp. 110-125.
- Tecle, Aregai. 1988. Choice of multicriterion decision making techniques for watershed management. Unpublished Ph.D. dissertation, The University of Arizona, Tucson, AZ 85721.

Tecle, Aregai, and Lucien Duckstein. 1989. Multicriterion analysis of international water resource projects. Presented at the Multicriterion Decision Making: Application in Industry and Service Conference, Bangkok, Thailand, Dec. 6-8.

Tecle, Aregai, Martin M. Fogel, and Lucien Duckstein. 1988. Multicriterion analysis of forest watershed management alternatives. Water Resources Bulletin, 24(6): 1169-1178.

USDA Forest Service. 1977. The Beaver Creek program: Advancing forest and range resources management. Available from the Forest Supervisor, Coconino National Forest, 114 N. San Francisco St., Flagstaff, AZ 86001, 24p.

USDA Forest Service. 1982. National forest system land and resources management planning (amended), Title 36 Code of Federal Regulations Part 219. Published in the Federal Register, September 30, pp. 43026-43052.

Von Neumann, J., and O. Morgenstern. 1953. Theory of games and economic behaviour, 3rd ed., Princeton University Press, Princeton, N.J.

Zeleny, M. 1982. Multiple criteria decision making. McGraw-Hill, New York, NY. 563p.

Zeuthen, F. 1930. Problem of monopoly and economic warfare. Routledge and Kegan Paul, London, U.K.

Insect Pest Management Expert Systems in Multiresource Management of Ponderosa Pine¹

David W. Long and Michael R. Wagner²

Abstract.--Expert systems have received considerable attention in entomology research in the last few years. Some researchers look to this information technology with high hopes of improved computer based decision making. To others it is a new gimmick; a new toy for computer buffs. An overview of the concept of expert systems and how this technology can be useful to foresters is explored in this paper. Existing entomology expert systems are reviewed and possibility of integrating expert systems into the pest management decision process is discussed.

INTRODUCTION

Decision making in forest pest management is a complex procedure involving insect population models, theories, hunches, and voluminous biological information. Managers must evaluate problems of pest activity, estimate future effects of the insects and potential problems, develop possible management plans, consider the effect the plan will have on other resources, and select a final course of action. The effectiveness of all this activity is a function of how well the manager can obtain and make use of existing knowledge (Rykiel et al. 1984, Power 1988). Recent advances in modeling and simulating together with stepped up research have increased the quality and quantity of information available to the manager but access to the information remains difficult and interpreting it even harder (Rykiel et al. 1984).

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²David W. Long is a Graduate Research Assistant in the School of Forestry, Northern Arizona University, Flagstaff, AZ.

³Michael R. Wagner is an Associate Professor, School of Forestry, Northern Arizona University, Flagstaff, AZ.

In response to this problem, congress passed 3 laws in 1978 authorizing technology transfer by states, extension branches of land grant colleges and universities, and the USDA Forest Service. Shortly after this, the Forest Service expanded its Office of Technology Transfer to improve coordination with others and to strengthen its efforts (Muth and Hendee 1980). But the rate of knowledge acquisition is rising so fast that managers cannot keep up with the new information. Colleges and universities are asked to find ways to rapidly and effectively deliver this information to the managers.

The most promising means of information transfer is through computer technology. Computers have been accepted by the general public with remarkably little controversy (Mazur 1987) and it looks like computer use will increase in the future (Stone et al. 1986). Rauscher (1987) emphasized this point through a comparison with the industrial revolution: "The first industrial revolution was characterized by machines that enhanced our physical capacity to work, while the second industrial revolution (in process) is based on machines that enhance our mental capacity to do work".

Early computers were used for structured problems with fixed purposes. Computer systems were used in entomology to process data and information with programs such as file management, data base management, simulation models and management information systems (Coulson and Saunders 1987). But systems are needed which can deal with unstructured problem

solving. We need systems that not only provide access to the information but can integrate the information for use, interpret the information and can serve as a coach to guide the user in problem solving (Coulson and Saunders 1987). Work is in progress to develop software systems that mimic the deductive and inductive reasoning of a human expert. The systems are called Expert Systems.

In this paper we will describe what Expert Systems are, how they are made, and what use they can be in forest entomology decision making. We will review Expert Systems that have been developed for insect pest management and summarize what has been learned from this work. We will also discuss how Expert Systems fit in with the general scheme of decision making and suggest future needs for an efficient information transfer system.

Background of Expert System Development

Since the time computers were invented researchers have dreamed of making an intelligent system for problem solving. The term Artificial Intelligence (AI) was first used in 1956 by John McCarthy at Dartmouth College. One of the first AI programs was written in 1957 by Allen Newell and Herbert Simon of Carnegie-Mellon University and J. Clifford Shaw of the RAND Corporation. It was called General Problem Solver (Waldrop 1984). The idea was to mimic human problem solving techniques with the computer. But it failed miserably because of the combinatoric explosion from all the millions of possible combinations in the solution process. Even a simple game like checkers has 10^{40} possible sequences (Waldrop 1984).

In an attempt to mimic the human brain, early researchers experimented with program structures called neural nets (imitating the neurons of a human brain) (Forsythe 1984). The researchers were surprised at how big a problem they came up against. The hardware was nowhere near capable of imitating the 10 billion neurons of a human. So AI researchers started using "heuristics" or rules of thumb to reduce the number of possible choices. Specialized knowledge was needed to form the rules, and as research progressed, more and more knowledge was needed until in the mid 1970s the idea of intelligence had changed. The concept of ability to reason had given way to the concept of having lots of specific knowledge about lots of subjects as the most important aspect of intelligence (Waldrop 1984).

Researchers questioned if reasoning ability was really all that important to intelligence. An expert seemed to just look at a problem as a whole and see a solution. It was less a matter of reasoning than of recognition of patterns in a large memory store house of knowledge and experience. Experts seemed to use reasoning only on unfamiliar problems. Thus knowledge

programming came into the forefront of AI. The purest and most narrowly defined form of knowledge programming is Expert Systems (ExS) (Waldrop 1984).

Expert Systems

Definition

The definition we will use for ExS in this paper was given by Stone et al. (1986): "Expert Systems are computer programs that offer solutions to complex problems by mimicking human reasoning process (heuristics) and employing knowledge base of information extracted from human experts." ExS are different from conventional programs in that they maintain a clear separation between the knowledge base and the mechanism for applying that knowledge to a specific problem (Rauscher 1987). In conventional programs knowledge items are mixed in with the program control statements for the solution of one specific problem. ExS, however, have a knowledge base separate from the control program (inference engine). When a problem is put before the computer, the inference engine looks at the knowledge base for answers to questions needed to solve the problem. These systems are much more versatile than conventional programs since they have the ability to use the same knowledge base to solve more than one specific problems.

Advantages

Coulson and Saunders (1987) list several advantages of ExS over conventional programs. First, both objective (simulation models and technical information) and subjective (expert opinions) information can be maintained in the knowledge base. Second, since the inference engine that runs the ExS uses pattern matching instead of the standard encoded branching method, it is nonprocedural and more flexible. It can handle a wider range of questions. Third, the control program and knowledge base are separate which simplifies maintenance and updating of the ExS. Fourth, ExS can deal with imprecise and incomplete information. Fifth, ExS can explain the steps taken in problem solving to the user since it "remembers" the chain of reasoning used. Sixth, a user need not have any special expertise to use the system.

ExS Basics

The idea of ExS is not really profound. Basically, ExS tie together if/then statements to produce reasonable inferences. They work well if: 1. The problem is well bounded, 2. There are many empirical if/thens that lead to a correct solution, 3. The total number of if/thens is sufficient to bring you close to a right answer (Mazur 1987).

ExS can be divided into two types: Diagnosis ExS and Decision-aid ExS (Stone et al. 1986). Many pest management problems can be solved with ExS of the first type. Insect identification and finding the best insecticide to use are two examples. These systems often are easy to build and can in cases be little more than a glorified dichotomous key. Decision-aid ExS, however, are more complex and usually interact with a model or simulation program and interpret the results.

Why Bother With Expert Systems?

Expert Systems have been promoted by excited researchers as "potentially the biggest thing since the industrial revolution" (Cohen 1987), "one of the fastest growing computer technologies in the world today" (Stock 1988); and they "perform at the level of human experts" (Lemmon 1986). ExS are even placed in the category of "artificial intelligence" in the computer programming field. But perhaps it is a little too over played. As Mazur (1987) said in his address to the Forest Resources Symposium, "AI is overblown by 'hype', by exaggerated self advertisement". Machines cannot match the intuitive intelligence that human beings have (Dreyfus and Dreyfus 1986). Some ExS that have been developed are in reality quite simple. Many diagnosis type ExS can be accomplished by a simple look up table (Cohen 1987). One might wonder if it is a little overkill to use an expensive computer to do something a sheet of paper can do.

On the positive side, however, ExS can bridge the gap between researchers and field use by managers. Researchers are experts at developing models and using them in problem analysis. They develop complex models to understand concepts like dynamics of insect populations but have little time to teach the use of these models to personnel in the field. When a problem comes up, the manager must find how the simulation model can solve it or at least provide some aid in understanding the problem. This is where ExS can contribute greatly to the decision making process. They can keep the knowledge base and simulation programs hidden to the decision maker so he can get the information he wants and focus on the problem at hand without having to see the complex routines used to come up with the answer. The ExS can then interpret the result of the simulation models so non-expert managers can understand. Cohen (1987) put it another way: "ExS may be most useful in advising non-experts in that part of the domain of interest regarded by human experts as routine". If more depth of understanding is desired, the manager can then question the ExS how it comes up with its solution and why. A manager can be deeply involved with the decision process or allow the computer to do it all and just accept the output of the program.

ExS can encourage users to actively participate in the knowledge acquisition necessary to solve the problem. In a follow-up study of the potato leaf hopper ExS, PLEX, developed at Pennsylvania State University the ExS stimulated farmers to gather necessary extra data when using the system because the value of this information was made clear by the ExS (Rajotte et al. 1988). Rauscher (1987) discussed six ways ExS can help improve productivity: 1. Capturing, refining, packaging and distributing expertise, 2. Solving problems that exceed the ability of non-experts, 3. Solving problems where the required scope of knowledge exceeds any individuals, 4. Creating an organization memory, 5. Avoiding delays when crises occur, and 6. Conserving the time of human experts. Most experts are scarce and in high demand. They are a valuable source of information but their knowledge is perishable. Experts get sick, die, change jobs, and often simply have "bad days". ExS can record their valuable knowledge for a permanent record easily accessible and consistent from day to day. And small scale ExS can take over some of the more routine aspects of an expert's job (Stock 1987).

Development of an Expert System

A good summary of points to check when planning ExS is given by Stock (1988). Actual development consists of five stages: Problem identification, working with an expert to develop the basic concepts, formalizing these concepts into a form that can be used by the program, writing the computer code, and testing (Waterman 1986).

Problem identification is a critical step in developing ExS. The problem should be well defined, a manageable size, and require a human expert to solve. "Problems that involve incomplete data and require judgement, approximation, or opinion in their solution are not well suited to an Expert System's approach" (Stone et al. 1986). Stock (1987) listed several criteria for judging the suitability of a problem for ExS. Most successful systems fulfill many of the following criteria: 1. The expertise should be scarce and not easily passed to novices, 2. The problem domain should be narrow but highly specialized, and there should be a larger number of possible solutions to the problem than can be realistically and thoroughly considered by a human trying to solve the task, 3. The problem solution should require heuristics (logic rules instead of just a set of equations), 4. The scope of the problem must be constrained for initial work, 5. Experts must exist who can competently solve the problem, and one of these experts must be able and willing to co-operate with the development of the ExS, 6. There should be a clear financial justification for building the system, 7. Experts in the area should agree - controversial subjects are

not appropriate for ExS, and 8. Ample data, test cases, and potential users should be available for validity testing and acceptability testing of the system.

In the conceptualization stage the system developer and expert decide what concepts, relations, and problem solving strategies are necessary for the problems covered by the ExS. Decisions are also made concerning the level of detail needed for the knowledge base and if any problem solving constraints are necessary. At this stage, the system developer conducts an extensive literature review and interviews one or more experts to gather the knowledge, theories, and problem solving techniques and rules of thumb used for solving the problems covered by the ExS.

The formalization step involves the expression of the concepts and relations in a formal way that will allow them to be used within the framework of the ExS program. The knowledge gathered in the previous step must be translated from pages of notes, thoughts, and ideas to some format usable by the computer.

Implementation is the step of actually creating the ExS computer program. ExS contains a user interface, a knowledge base, and an inference engine (Stock 1987). The user interface is the part of the program that interacts with the user, usually in a natural language (ie. English). The knowledge base is a data base of appropriate facts and rules (heuristics). The rules are usually rules of good judgement used by the expert in problem analysis. Typically, rules follow a form similar to: If (fact) Then (conclusion). For example, If the tree has tiny holes in the bark Then look for bark beetle larvae. The inference engine controls the reasoning process and interacts with the user interface and knowledge base to maintain the flow of the program.

Finally, the system is tested for accuracy and usability. Several phases of testing should be included at various levels. Rajotte et al. (1988) list a few as follows. The developers must check the system for system errors and the knowledge base to make sure it is accurate. A set of problems with known solutions should be set before the system and human experts to compare the solutions obtained. Next, the system should be checked by colleagues who are experts in the same field as the ExS. Then a pilot study should be arranged using a sample of the potential users to make sure it is appropriate to their needs. Finally the software is prepared for general use after all errors and problems are corrected. But even after release, the system must be monitored to obtain suggestions for improvement and update the knowledge base as new information is produced by researchers.

Application to Forestry

ExS can benefit forestry in three main ways: as decision making aids, forest science librarian, and in forestry education (Rauscher 1987).

The forest manager can use ExS in place of or in addition to a staff of specialists. When experts are rare and in high demand, ExS can relieve a lot of pressure on both the experts and managers. The final decision must be made by the manager who evaluates the results of the ExS and recommendations made by his staff.

Getting the right information from the research laboratories to the managers in a reasonable length of time and in a usable form is quite difficult and is getting harder with the increase of information available. Keeping track of all this information is becoming impossible (Power 1988, Rajotte et al. 1988, Rauscher 1987, Rykiel et al. 1984). ExS are a natural vehicle to do this especially if they help with interpreting the information and structuring it in a way that is easily used by the managers. ExS can help by taking on the role of librarian to help manage all this knowledge. Duties could include assembling, cataloging, storing and retrieving information, determining the quality of the information, and possibly, determining what information is still missing.

As an aid to forestry education, ExS can educate the general public about forestry issues, train new forest managers and technicians for specific jobs, and aid personnel in their jobs by serving as handbooks, or check lists to increase their performance (Rauscher 1987).

Sample Systems

In forest entomology, ExS have been or are being developed for taxonomic identification, diagnosis, pesticide recommendation, and delivery of simulation models (table 1).

SYTEX (Systematics Expert System) was built to relieve pressure on taxonomists who often are flooded with specimens to identify from across the US and world and to provide an alternative to dichotomous keys (Stone et al. 1986). However, due to the size of the problem of developing the program, only one species was used for the key, Signipbora spp. Ashmead. This highly restricted key may not reduce the taxonomist's work load, but it is a good start in the right direction.

BIPS and ISPBEX were developed at Texas A&M University for diagnosis and prediction of bark beetle related forest management problems (Rauscher 1987).

Table 1.--Expert systems developed for forest insect pest management.

Program	Purpose	Source
INSEX	Recommend insecticides for western forest insect control	Coulson, Robert N., Texas A&M University (unpublished).
ISPBEX	Southern pine bark beetle decision support system	Rykiel, et al., 1984.
SYSTEX	Insect identification	Stone, et al., 1986.
HOPPER	Western rangeland grass-hopper control	Kemp, et al., 1988.
PMDS	Aid in insect population model development	Logan. 1988. Environmental Entomology 17(2).
BIPS	Diagnose & predict bark beetle problems	D.K. Loh, Texas A&M Univ. (unpublished).
PREDICT	Diagnosis problems and assess hazards for red pine insects and disease in Wisconsin	Schmoldt and Martin. 1989.

PREDICT was developed by Daniel Schmoldt of the USFS for diagnosing problems and assessing hazards for red pine insects and diseases in Wisconsin (Schmoldt & Martin 1986,1989). In the diagnosis mode, the user provides information about the stand characteristics and identifies symptoms from a set of menus. The ExS then identifies the causal agent. A second mode, preventive consultation mode, lists various insects and pathogens to be alert for under the stand characteristics identified by the user.

INSEX is an ExS developed by Robert Coulson at Texas A&M University that recommends insecticides for Western forest insect control (Rauscher 1987).

HOPPER is an ExS for western rangeland grasshopper control developed by the USFS (Kemp et al. 1988). The user is questioned about site information, present development stage of the grasshoppers, and the management objective (ie. to save forage), then the system makes a treatment recommendation and gives a benefit/cost ratio for the treatment.

PMDS (Pest Model Design System) is being developed by Jesse Logan of Colorado State University (Logan 1988) as a research tool for entomologists. The goal of the project is to build a program capable of building an insect population model from life history information. The system should reduce the time and expense of developing models that fit in its domain.

What Has Been Learned?

Although ExS have enjoyed success in other fields, they are slow in getting a foothold in forest entomology (Schmoldt and Martin 1986). Two main problem areas slow the process: 1. ExS are not totally suited for natural systems problems and 2. there is a gap in understanding between the researchers/developers and the final users of the systems (technology transfer problems).

Suitability

Research in ExS has a history of less than 20 years and very few systems have been developed in the field of entomology. Rule-based ExS are not well suited to natural systems management for 2 reasons: Rules are not well suited to provide advice in natural system problems and the management process itself is too broad a problem to be suitable for ExS (Coulson et al. 1987). Rule based ExS use inference schemes which are too shallow to provide much more than searches and conflict resolution strategies (Coulson et al. 1987). Application of ExS to resource management is complicated by the existence of multiple experts, uncertainty characteristic of biological and economic data, large data bases, and a knowledge domain that is tied to a changing landscape (Coulson et al. 1987).

Since natural systems are dynamic and not completely understood, scientists tend to try explaining natural phenomena in terms of causa-

tion, not correlation. Rules are not well suited to describe this causative knowledge so deeper knowledge bases are being developed now using structures such as frames and semantic nets to describe the deep knowledge of causation (Coulson et al. 1987). Attempts to apply general theories tend to generate unmanageably large problems for existing ExS technology.

One of the critical elements of ExS is a large knowledge base. Most existing ExS in pest management have been developed for systems well understood and where a lot of data is already in existence such as cotton farming (Lemmon 1986) and bark beetle management (Rykiel et al. 1984). More knowledge on the biology and ecology of forest insects will probably be needed in order to develop good ExS.

It takes a long time to develop an Expert System. Even a prototype of a subset of the problem may take 6 months (Stock 1987). Current projects are getting too large and complex for the traditional 1 student projects (ExS PREDICT took a PhD student 4 years to develop), so the tendency is to skim significant results off the surface of the research and ignore possibilities which lie deeper (Cohen 1987). The temptation is to go for the new and exotic programming at the expense of a completely rounded research project.

Technology Transfer

The inapplicability of ExS to natural systems and insufficient knowledge base are tough problems, but the understanding gap between researchers and users should be easier to solve. Programmers usually do not have to use their programs in the field so in order to develop practical programs they need to understand the user's needs and abilities. In developing the program they should go out to where the programs will be used and interact with the users in their own environment; learn the limitations of the user and understand his problems. The users want information consistent with their conception of the problem. They want it fast, accurate, and obtainable in a user friendly atmosphere without the need of a computer person to help them (Baskerville and Moore 1988). This importance of technology transfer was impressed on researchers at Texas A&M when a southern pine beetle decision support system package was provided to the United States Forest Service but never used (Coulson et al. 1989).

Flexibility

Researchers often get preoccupied with the problem at hand and ignore the needs of the end user. Users are often frustrated when forced into a fixed format by a computer program to answer "the" question expected by the program (Baskerville and Moore 1988). When talking with a human expert, they can ask the questions they

want instead of only listening to problems the expert wants to talk about. This flexibility should be written into ExS too.

One person cannot be an expert in all areas of ExS development. Programming, research, the user interface, and system planning are all important. Therefore a committee should work together in developing a program: the management, researchers, and decision makers (Baskerville and Moore 1988, Rajotte et al. 1988).

Future

Future ExS research should concentrated on two main areas: Improving the user interface and adapting ExS technology to problems in working with natural systems.

User Interface

One of the big frustrations users have with ExS is the inability to ask the questions they want. ExS are programmed to answer a narrow range of questions and the user is only given these questions to choose from for his problem. In consulting a human expert, a manager can ask a lot of questions not directly related to the main problem in order to fix in his mind his real problem. The expert can discuss general problems and theories with the manager before focusing on specific solutions to the problem. The interaction is informal and comfortable to the manager. A partial solution to the user interface problem is presented by Rykiel et al. (1984). They developed a program called FERRET, a problem analysis program. It analyzes the user's question and translates it to a form useable to the program. However, its use is still restricted since the user must choose selections from menus given by the computer to present his question instead of simply asking the question in common English like he would to a human expert.

Another problem that needs more work is adapting to the varying levels of interest exhibited by the users. Some users simply want "The Answer" so they can go on with their work. Others wish to play with the system doing "what ifs" and learning why the ExS came up with its answer. Rykiel et al. (1984) describe a decision support system for management of southern pine beetle which has 3 levels of problem structure. In the first level, the user can have direct access to data and models. All inputs are supplied by the user. In the second level, the computer tells the user what models are necessary and what inputs are needed to solve his problem. The user inputs the information and runs the models desired. The third level is the least participate in by the user. The system runs automatically to solve the problem.

Adapting Technology

Expansion of research in use of structures such as frames and semantic nets for knowledge base representation should be productive. Since natural systems are constantly changing and our knowledge and understanding of these systems is increasing, ExS should focus on specific narrow range problems in order to keep them small and easily updated as new knowledge is gained.

Technology Transfer

This leads to our last point, that ExS should be considered as small units to be plugged into a larger decision support system. Some work has already been done in this direction. Hearn and Brook (1988) describe a concept called Integrated Expert Systems. In this system, an executive program manages sub-programs consisting of ExS shell, Data Base Management system, and a system for numerical calculations. The Canadian Forest Service is interested in using ExS in their decision support system called FIDSINFOBASE to handle the nation-wide data base which is integrated with a Geographic Information System (Power 1988). ExS could be plugged in wherever needed and remain invisible to the users.

A general decision support system (DSS) should be developed which accepts ExS modules that can be plugged in and taken out as necessary. This DSS must be implemented by experts in user interface since the user will interact with the DSS program. The ExS plug-in modules would essentially be invisible to the user.

Research staffs are not trained to develop and maintain software to industry standards (Hearn and Brook 1988). Their interest is not focused on the knit-picky stuff like screen color or placement of prompts which are so important for user satisfaction. They are needed for developing prototypes, but the final form of the ExS to be used by managers should be programmed by computer programmers familiar with the industry standards for user interface. These programmers can efficiently present the information of the ExS to the user in a format comfortable to him and carry out the updating of the ExS as new information or a change in knowledge about the problem changes. The word processing industry, for instance, benefitted by programmers who took the initial concept and wrote new word processors that are more user friendly.

Until recently, AI involved large investment of money, time, and personnel, but software shells have been developed that make the completion of a prototype easier (Stock 1987). Researchers using these shells can produce prototype ExS using the most up to date knowledge and technology. They do this well. But psychologists, human factors engineers, sociologists and many others may have signifi-

cant contributions to the system before it is ready for release to the public (Stock 1987). The developers of the SIRATAC pest management system in Australia learned that releasing software for commercial use involved a lot more than having a working system (Hearn and Brook 1988). They grossly underestimated the staff needed for trouble shooting, user education and maintenance of the computer program. Maintenance problems of the software were compounded by the fact that it was written by biologist researchers who were not programming up to the industry standards. They finally decided to have the program rewritten by industry professionals.

CONCLUSION

Expert systems have been hyped up greatly with implications that they are more efficient, accurate, and consistent than a human expert. Tests have shown that this is indeed often the case, however, rule based ExS are not well suited to many of the problems confronted by pest managers such as those involving controversy or with little existing knowledge. Attempts to force ExS to deal with these problems will end up with frustration. New ExS that are frame based instead of rule based are being developed and have potential use for these problem areas. Where there are not many biological data available or knowledge about the problem solution (i.e., experts do not know what is best or do not agree with each other) then ExS are not appropriate.

ExS technology has been around for several years now and has proven its worth. With the introduction of ExS shells to the market place, development of ExS has been simplified and it is probably no longer a science. There is not a good pay off for universities to develop ExS unless they wish to study the science involved in the background of the development such as efficiency of the systems, cost/benefit analysis, or better methods of knowledge base construction. But once the methodology and utility of ExS has been established, the universities should give the problem to other agencies to do the development work. A technology transfer specialist could then crank out the ExS using the field data, models, and methodologies established by the university researchers.

Where should we go next? Universities should continue to research the biological aspects needed for ExS and develop better methodologies for ExS development. Other agencies should do the actual ExS development with emphasis on sound technology transfer schemes between researchers and users. These agencies will conduct cost/benefit analysis to determine which ExS are worth developing and to what extent. If we all stick to our role in the process and remember the overall goal, we will not let the new technology blind us from reality.

LITERATURE CITED

- Baskerville, G. and T. Moore. 1988. Forest information systems that really work. *The Forestry Chronicle*. April p.136-140.
- Cohen, Paul R. 1987. A brief history and prospects of knowledge systems in resource management. *Compiler* 5(5):7-13.
- Coulson, Robert N. and Michael C. Saunders. 1987. Computer-assisted decision-making as applied to entomology. *Annual Review of Entomology*. 32:415-37.
- Coulson, Robert N., L. Joseph Folse, and Douglas K. Loh. 1987. Artificial intelligence and natural resource management. *Science* 237:262-67.
- Coulson, Robert N., Michael C. Saunders, Douglas K. Loh, Forrest L. Oliveria, David Drummond, Patrick J. Barry, and Kenneth M. Swain. 1989. Knowledge system environment for integrated pest management in forest landscapes: The southern pine beetle (Coleoptera: Scolytidae). *Bulletin of the Entomological Society of America* 35(2):26-32.
- Dreyfus, Hubert and Stuart Dreyfus. 1986. Why expert systems do not exhibit expertise. *IEEE Expert*. Summer p.86-90.
- Forsythe, Richard. 1984. Expert systems principles and case studies. Chapman and Hall, New York, NY.
- Hearn, A.B. and K.D. Brook. 1988. A case study of the application of a knowledge based system to cotton pest management: A tale of two technologies. *PennState College of Agriculture Entomology working papers* 1988 1(2): Approaches to the development and implementation of knowledge based systems in agriculture and natural resources: a global perspective. Symposium presented at the 1988 Entomological Society of America National Conference and Exhibition, Louisville, Kentucky, December 7, 1988. Calvin, D.D., E.G. Rajotte, and M.C. Saunders organizers.
- Kemp, William P., Jerome A. Onsager, and Hal E. Lemmon. 1988. Rangeland grasshopper treatment selection: An expert system for decision support in resource management. *AI Applications* 2(4):1-8.
- Lemmon, Hal. 1986. Comax: An expert system for cotton crop management. *Science* 233:29-33.
- Logan, Jesse A. 1988. Toward an expert system for development of pest simulation models. *Environmental Entomology* 17(2):359-376.
- Mazur, Allan. 1987. Artificial stupidity. *Compiler* 5(5):4-6.
- Muth, Robert M. and John C. Hendee. 1980. Technology transfer and human behavior. *Journal of Forestry*. March p.141-144.
- Plant, R.E., L.T. Wilson, P.B. Goodell, T.A. Kerby, and L.J. Zelinski. 1988. Development and implementation of expert system based management programs in California. *PennState College of Agriculture Entomology working papers* 1988 1(2): Approaches to the development and implementation of knowledge based systems in agriculture and natural resources: a global perspective. Symposium presented at the 1988 Entomological Society of America National Conference and Exhibition, Louisville, Kentucky, December 7, 1988. Calvin, D.D., E.G. Rajotte, and M.C. Saunders organizers.
- Power, J.M. 1988. Decision support systems for the forest insect and disease survey and for pest management. *The Forestry Chronicle*. Fall p.132-135.
- Rajotte, E.G., T. Bowser, C. Sachs, W. Musser, M.C. Saunders, D.D. Calvin, P.H. Heinemann, L.A. Hull, R.M. Crassweller, and J.W. Travis. 1988. Putting expert systems into the field: Some results of a pilot implementation program. *PennState College of Agriculture Entomology working papers* 1988 1(2): Approaches to the development and implementation of knowledge based systems in agriculture and natural resources: a global perspective. Symposium presented at the 1988 Entomological Society of America National Conference and Exhibition, Louisville, Kentucky, December 7, 1988. Calvin, D.D., E.G. Rajotte, and M.C. Saunders organizers.
- Rauscher, H. Michael. 1987. Expert systems for natural resources management. *Compiler* 5(5):19-27.
- Rykiel, E.J., M.C. Saunders, T.L. Wagner, D.K. Loh, R.H. Turnbow, L.C. Hu, P.E. Pulley, and R.N. Coulson. 1984. Computer-aided decision making and information accessing in pest management systems, with emphasis on the southern pine beetle (Coleoptera: Scolytidae). *Journal of Economic Entomology* 77(5): 1073-82.
- Schmoltdt, Daniel L., and George L. Martin. 1986. Expert systems in forestry: Utilizing information and expertise for decision making. *Computers and Electronics in Agriculture* 1:233-250.
- Schmoltdt, Daniel L., and George L. Martin. 1989. Development and evaluation of an expert system for diagnosing pest damage of red pine in Wisconsin. *Forest Science* 35(2): 364-387.
- Stage, Albert R., Nicholas L. Crookston, Marc R. Wiitala. 1986. Procedures for including pest management activities in forest planning using present or simplified planning models. In: *Proceedings of the workshop on lessons from using FORPLAN*; April 29-May 1, 1986; Denver, CO. Washington, DC: USDA Forest Service, Land Management Planning Systems; Bailey, R.G. proc. tech. coord. 268 p.
- Stock, Molly. 1987. AI expert systems: an overview. *AI Applications* 1(1):9-17.
- Stock, Molly. 1988. Planning expert system projects. *AI Applications* 2(4):9-16.
- Stone, N.D., R.N. Coulson, R.E. Frisbie, and D.K. Loh. 1986. Expert systems in entomology: Three approaches to problem solving. *Bulletin of the Entomological Society of America* 32(3): 161-166.

- Waldrop, M.Mitchell. 1984. The necessity of knowledge. Science 223:1279-82.
- Waterman, Donald. A. 1986. A guide to expert systems. Addison-Wesley Publishing Company, Reading, Massachusettes.

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WILDHARE: A Wildlife Habitat Relationships Data Model for Southwestern Ponderosa Pine¹

David R. Patton² and Kieth E. Severson³

Abstract.--Wildlife habitat can be described completely by a system of attributes and relations in a relational database. A habitat relationships data model has been developed for ponderosa pine that includes four basic relations and 33 attributes for 250 wildlife species.

INTRODUCTION

The Forest and Rangeland Renewable Resources Planning Act of 1974 gave the Forest Service responsibility for inventorying the Nation's resources, including fish and wildlife habitat. Because a comprehensive inventory had not been made previously, no detailed guidelines were available on the types or format of data to be collected. In addition, computer software had not been developed to store and retrieve wildlife habitat data. To overcome these problems, the Rocky Mountain Forest and Range Experiment Station developed a wildlife habitat database for the Southwest. This effort resulted in a database (RUNWILD) for a mainframe computer (Patton 1978).

While RUNWILD was a useful tool, it soon became apparent that large capacity microcomputers (>20 megabytes) along with new database software would make data storage and retrieval easier, particularly if the storage scheme

conformed to relational theory (Codd 1970). Relational theory guides how data can be depicted and linked in a database. Our paper reports on a general relationships data model linking wildlife species to habitat characteristics in the ponderosa pine forest type.

Southwestern ponderosa pine was selected as a sample forest type for developing a habitat relationships data model because a large amount of wildlife data is available for the type; it is a major commercial species, and the type contains over 250 wildlife species of all life-forms (amphibians, birds, fish, mammals, and reptiles). In developing a relationships model, we interacted with biologists at the region, forest, and district level. Their specific request was to describe the physical characteristics of various vegetation types and to associate each wildlife species with the use of these characteristics for food or cover.

WILDLIFE HABITAT RELATIONSHIPS

Wildlife habitat relationships (WHR) is a systems approach to understanding how animals use vegetation, plants, and landscape features for food and cover. It is a way of thinking about the conditions and processes involved in the complex of plant-animal interactions. WHR programs have been in progress since the late 1970's (Patton 1978, Thomas 1979, Verner and Boss 1980) but associating animals with their habitat is as old as the wildlife profession.

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²David R. Patton is Professor, Forest Wildlife Ecology, School of Forestry, Northern Arizona University, Flagstaff, Ariz.

³Kieth E. Severson is Principal Wildlife Research Biologist, USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Arizona State University Campus, Tempe, Ariz.

A general classification of North American mammals and birds by forest habitat preference was developed by Yeager (1961). Birds and mammals were placed into three groups according to whether they are primarily associated with forest or brushland, secondarily associated with forest or brushland, or woody cover not used or only rarely used. The importance of this form of classification is greater today than it was over 40 years ago when Taylor (1940) stated:

"The ecologist capable of arranging all species of mammals and birds, or all vertebrates or animals, into a habitat classification fully considerate of vegetation, terrain, water, elevation, exposure, latitude, and climatic factors would indeed provide a vast fund of useful knowledge."

Because of the large amount of information accumulating in books, journals, and government publications, detailed information is now available to include in a habitat classification scheme as suggested by Taylor.

Describing Habitat

The relationships between animals and habitat can be described completely by using a system of attributes and relations. An attribute is a fact about

an inherent physical characteristic, property, measurement, or quality of an animal, plant or habitat. The term relation refers to a collection of facts (attributes) describing the same subject.

One way to understand attributes and relations is to consider a matrix table as the relation and columns in the matrix as attributes (fig. 1A). Cells within attributes contain information about the attribute characteristic. For example, the attributes in a relation could be Species, Vegetation type, Stand structure, Use, and Season (fig. 1B). One row of data for the attribute cells could be deer, ponderosa pine, mature, cover, and winter, in that order.

All the attributes form a relation which might be named "WILDLIFE". Figure 1B provides data indicating that deer and squirrels both use mature ponderosa pine for cover, but squirrels also use ponderosa pine for food. Stand structure can be divided further for additional detail. In this manner, a habitat relationships model can be formulated for many species and many habitat characteristics.

THE PONDEROSA PINE MODEL

For the ponderosa pine forest type and other habitats in general, four

===== A

: RELATION	:
: Attribute	: Attribute : Attribute : Attribute :
: Row	:-----:-----:-----> :
: cell	: cell : :

===== B

: WILDLIFE	:
: Species	: Vegetation : Stand : : :
: Species	: Type : Structure: Use : Season :
: Deer	: PP : Mature : Cover : Yearlong :
: Squirrel	: PP : Mature : Cover : Yearlong :
: Squirrel	: PP : Mature : Food : Yearlong :

Figure 1.--Habitat attributes and relations can be defined in tables and columns.

relations form the basic data model: These are SPECIES, HABITAT, ECOS, and AREA (fig. 2) in a database named "WILDHARE"--an acronym for Wildlife Habitat Relationships. Relation names have all capital letters. Attribute names are lower case with the first letter capitalized. Descriptions of relations, attributes and their menus are contained in table 1.

Data in the SPECIES relation applicable to a particular animal are entered only once. The SPECIES relation is also the core relation for WILDHARE because data in the other relations ultimately are linked back to this

relation. By entering a species common name in Cname, entries must be made for the other attributes until all the cells in each attribute are filled and one row is complete. For example, the following data could be included in the HABITAT relation:

Cname: Mule deer
 Series: Ponderosa pine
 Reuse: Cover area
 Level1: Tree stand
 Level2: Dbh 11.0-13.9
 Level3: Dense, little or no understory
 Level4: Single story
 Value: Moderate

WILDHARE DATA MODEL

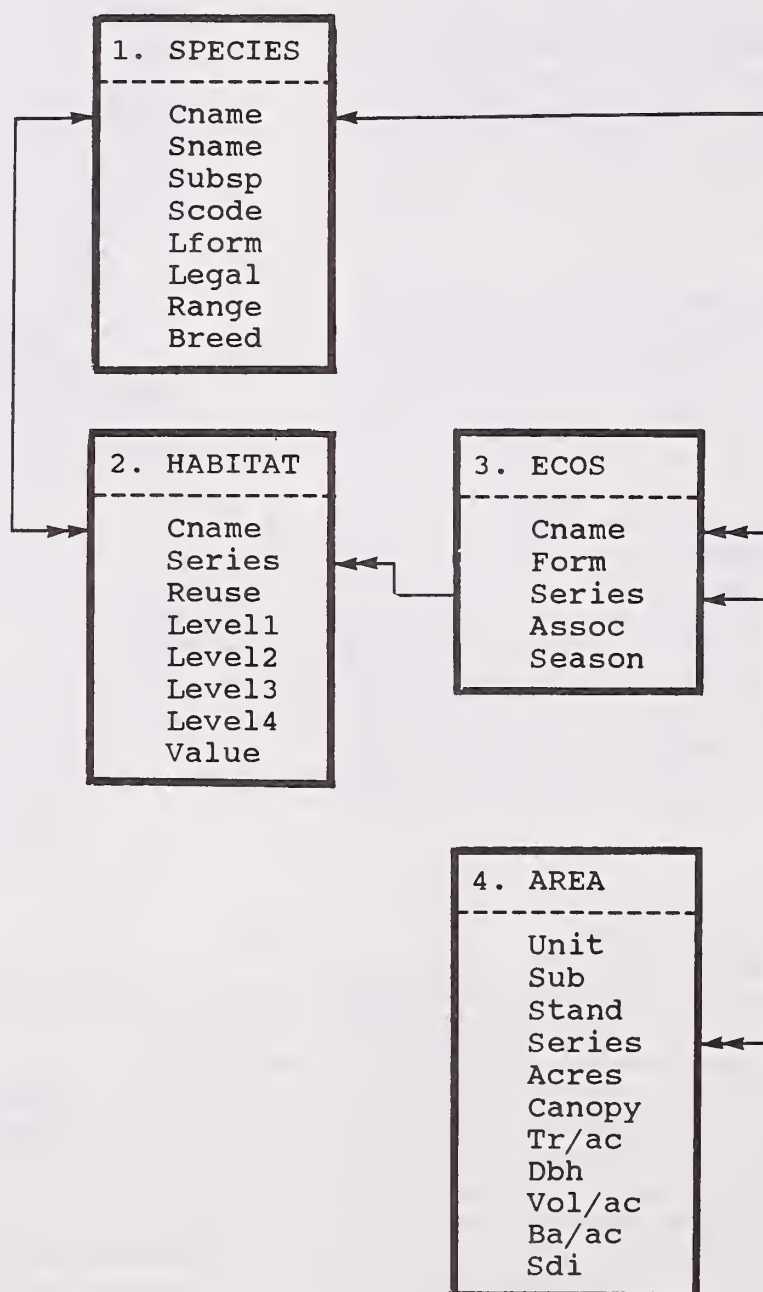


Figure 2.--A habitat relationships data model for the ponderosa pine forest type.

Table 1.--Relations and attributes in WILDHARE.

RELATION	Attribute ¹
1. SPECIES	<ol style="list-style-type: none"> 1. Cname (30) (Common name) 2. Sname (30) (Scientific name) 3. Subsp (15) (Subspecies) 4. Scode (9) (Scientific code) 5. Lform (2) (Life-form) <ul style="list-style-type: none"> AM = Amphibian BI = Bird FI = Fish MA = Mammal RE = Reptile IN = Invertebrate 6. Legal (2) (Legal status) <ul style="list-style-type: none"> FL = Federal listed SL = State listed GA = Game animal FB = Furbearer NG = Nongame 7. Range (15) (Home range) <ul style="list-style-type: none"> User defined 8. Breed (6) (Breeding season) <ul style="list-style-type: none"> Spring (Mar-May) Summer (Jun-Aug) Fall (Sep-Nov) Winter (Dec-Feb)
2. HABITAT	<ol style="list-style-type: none"> 1. Cname (30) (Common name) 2. Series (2) (Vegetation type) 3. Reuse (7) (How physical resources are used) <ul style="list-style-type: none"> Feeding (area) Cover (area) Food (item) Shelter Special (requirements) 4. Level1 (20) (1st level use) <ul style="list-style-type: none"> <u>Feeding and Cover area</u> <ul style="list-style-type: none"> Air Opening Topography Tree stand Water <u>Food item</u> <ul style="list-style-type: none"> Vertebrates Tree-shrub parts Herbaceous parts Aquatic Artifacts Fungi Arthropods

Shelter
Live tree
Snag
Cave
Log-stump
Ground
Understory
Woody debris
Litter
Rock fissures
Special requirements
User defined

5. Level2 (20) (2nd level use)

Air
Over water
Over vegetation
Over all terrain

Opening
Grass-forbs
Shrubs
Small trees (<5'-1.9)
Single tree

Topography
Cliff-ledge
Talus slope
Canyon bottom
Rock outcrop

Tree stand
Dbh 5'-1.9"
Dbh 2.0-4.9 (Sapling)
Dbh 5.0-7.9 (Small tree)
Dbh 8.0-10.9 (Small-medium tree)
Dbh 11.0-13.9 (Medium tree)
Dbh 14.0-16.9 (Medium-large tree)
Dbh 17.0-19.9 (Large tree)
Dbh 20+ (Old trees, Old growth)

Water
Seeps-springs
Streams-rivers
Ponds-lakes
Bank
Marsh
Rain pools

Vertebrates
Amphibians
Birds
Fish
Small mammals
Medium-large mammals
Reptiles

Tree-shrub parts
Cones
Twigs
Buds
Pollen
Leaves
Roots
Needles
Acorns
Bark

Soft fruits
Nuts
Seeds
Sap

Herbaceous
Flowers
Shoots
Nectar
Misc. vegetation
Honey
Grass
Forbs
Woody stems (browse)

Aquatics
Submergents
Emergents
Algae
Plankton
Aquatic insects

Artifacts
Carrion
Eggs
Bones
Garbage

Fungi
Mistletoe
Hypogeous fungi
Shelf fungi

Arthropods
Flying insects
Insect larvae
Crawling insects
Crustaceans
Snails
Spiders
Worms

Shelter
Nest
Bed
Burrow
Roost
Cavity
Under bark
Bunchgrass
Brush

6. Level3 (15) (3rd level use)

Opening
Dry
Moist-wet

Water
Warm
Intermediate
Cold

Tree stand

THa = Thin, little or no understory
THb = Thin, understory of grass-forbs
THc = Thin, understory of shrubs
THd = Thin, understory of small trees
MOa = Moderate, little or no understory
MOb = Moderate, understory of grass-forbs
MOc = Moderate, understory of shrubs
MOD = Moderate, understory of small trees
DEa = Dense, little or no understory
DEb = Dense, understory of grass-forbs
DEc = Dense, understory of shrubs
DEd = Dense, understory of small trees

7. Level4 (15) (4th level use)

Opening or Shelter

Sandy soil
Rocky soil
Moist soil

Tree stand

Single (story)
Multiple (story)

Water

Milky-muddy

8. Value (1) (Degree of preference when available)

5 = High use
4 = Moderately high
3 = Moderate
2 = Moderately low
1 = Low
* = Used (value unknown)

3. ECOS

1. Cname (30) (Common name)

2. Form (2) (Vegetation formation)

FO = Forest

3. Series (2) (Vegetation series).

PP = Ponderosa pine

4. Assoc (2) (Association with Series)

HA = Considered typical habitat
FR = Occurs but is fringe habitat
RA = Rarely occurs in type

5. Season (2) (Presence in SERIES)

YL = Yearlong resident
SU = Summer
WI = Winter
SM = Seasonal movement (up-down slope)

4. AREA (To be developed for each local area)

DEFINITIONS

Opening: <10% canopy, or vegetation not in trees

TH = Thin: 11-40% overstory
MO = Moderate: 41-70% overstory
DE = Dense: >70% overstory

a = Little or no understory
b = Grass-forb
c = Shrubs
d = Small trees (5' ht-1.9" Dbh)

* = This symbol can be used in the database for any attribute that is unknown or not yet determined.

¹Number in parenthesis is number of spaces allocated to attribute.

Text data are generally used to describe attributes but in some cases codes are used instead, for example, PP = ponderosa pine, FO = forest, etc. Entries or values are selected from a menu for each attribute. In developing attribute characteristics, statements are used that describe physical habitat either quantitatively or qualitatively. Other attributes (Level5, etc.) can be added if more detail is needed. In the example above, values for all 8 attributes contribute one row of information, in one relation.

The ECOS relation (ecosystem) provides information on the adaptability of species to different vegetation types. Since a given species can be found in several types, the ECOS relation will contain duplicate data for some attribute cells but no two rows of data will be identical--that is, one attribute cell will always be different in each row.

In the AREA relation, all attributes are associated with Stand. Stand is part of a subunit (Sub) and subunit is part of another unit (Unit). As a result of these identifiers, numerical totals such as volume per acre, basal area per acre, or total acres can be computed for a management unit or subunit. Computations and statistical analysis can be made for the other quantified attributes.

How The System Works

Relations have key attributes for retrieving data from more than one relation at the same time. Data from one relation is linked to data in other

relations by direct and indirect routes. Direct links between SPECIES, HABITAT, and ECOS are provided by Cname and between HABITAT, ECOS, and AREA by Series. An example of a question that can be asked using the direct link is: What endangered species (Legal and Cname in SPECIES) are found in ponderosa pine yearlong (Cname, Series and Assoc in ECOS)?

Since the Series attribute is in HABITAT, ECOS and AREA, and Cname is in SPECIES, HABITAT and ECOS then SPECIES and AREA are indirectly linked through either HABITAT or ECOS. This indirect link provides the route for associating data in SPECIES with data in AREA. For example: What wildlife species (Cname in SPECIES) should be found in a management unit (Unit in AREA) containing ponderosa pine (Series in ECOS)? Data can also be retrieved from one relation. For example, the statement to be made from the one row of data in the HABITAT relation defined previously is: "Dense, single story ponderosa pine stands, ranging from 11-14 inches dbh, with little or no understory have a moderate cover value for mule deer".

In the past we have used a species code (Scode) developed from the scientific name as a unique link between relations because of a need to conserve space. Since space is no longer a critical problem for large capacity microcomputers, common name (Cname) is a good link to use because it is more meaningful to biologists than a code. Scode is included in the SPECIES relation for reference.

The relationships data model is to be used with relational database

software.⁴ Information is retrieved or manipulated from WILDHARE using commands common to databases conforming to relational theory. While the WILDHARE habitat relationships model contains only four relations, its utility is in the combinations of attribute characteristics associating an animal with physical habitat and the value of that association if it is known.

FUTURE DEVELOPMENT

The basic habitat relationships data model will need refining as we add more wildlife species and their physical habitat requirements. Our goal is to include wildlife species for other forest types in the Southwest. Future development of WILDHARE will be to include it as a module for the Decision Support System (DSS) now being developed in the School of Forestry at Northern Arizona University (Covington et al. 1989). The DSS incorporates a GIS and a growth and yield model that will make WILDHARE a practical tool to compare management alternatives.

LITERATURE CITED

Codd, E. F. 1970. A relational model of data for large shared databanks. Communications of the ACM 13(6): June.

⁴WILDHARE was formatted in Microrim's R:Base for DOS with artificial intelligence software (Clout).

Covington, W. W, D. B. Wood, D. L. Young, D. P. Dykstra, and L. D. Garrett. 1988. TEAMS: A decision support system for multiresource management. Journal of Forestry 86(6):25-3.

Patton, D. R. 1978. RUNWILD, a storage and retrieval system for wildlife habitat information. USDA Forest Service Gen. Tech. Rep. RM-51, 8 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Thomas, J. W., ed. 1979. Wildlife habitats in managed forests, the Blue Mountains of Oregon and Washington. USDA Agric. Handb. 553, 512 p. Washington D.C.

Taylor, W. P. 1940. Ecological classification of the mammals and birds of Walker County, Texas, and some adjoining areas. Transactions of the North American Wildlife Conference 5:170-176.

Verner, J., and A. Boss. 1980. California wildlife and their habitats: Western Sierra Nevada. USDA Forest Service Gen. Tech. Rep. PSW-37, 439 p. Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif.

Yeager, L. E. 1961. Classification of North American mammals and birds according to forest habitat preference. Journal of Forestry 59:671-674.

Registrants for: MULTIRESOURCE MANAGEMENT OF PONDEROSA PINE FORESTS

A

Dr. Celedonio Aguirre-Bravo
Professor
Division De Forestales
Universidad Autonoma Chapingo
Chapingo, Texcoco,
Edo. De Mexico, CP56230
MEXICO
(595)4-2462

Clifford J. Anable
GIS Coordinator
USDI-Bureau of Indian Affairs
Fort Apache Agency
P.O. Box 560
Whiteriver, AZ 85941
(602)338-4364

Steve Andariese - Presenter
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Phillip Anderson
Director,
The Precambrian Research Institute
810 Owens Lane
Payson, AZ 85541

R. Scott Anderson - Presenter
Bilby Research Center
P.O. Box 6013
Flagstaff, AZ 86011
(602)523-5821

Zoran Antonijevic - Student Assistant
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Chuck Avery
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

B

Margaret Bailey - Student Assistant
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011

Jack B. Ball
2386 N. Whispering Pines
Flagstaff, AZ 86001
(602)527-8014

Catherine Balzano
Water Resources Specialist
Arizona Dept. of Water Resources
15 S. 15th Ave.
Phoenix, AZ 85007
(602)542-1546

Douglas K. Barbar
Administrative Forester
USDA-Forest Service
Apache-Sitgreaves N.F.
P.O. Box 640
Springerville, AZ 85938
(602)527-7400

Susan L. Bartell
Supervisory Forester
USDA Forest Service
Coconino National Forest
2323 E. Greenlaw Ln.
Flagstaff, AZ 86004

Richard L. Bassett - Moderator
Regional Silviculturist
USDA - Forest Service
Region 3
517 Gold Ave., SW
Albuquerque, NM 87102
(505)842-3480

Mary Beckman-Najera
Silviculturist
USDA Forest Service
Reserve Ranger District
Box 170
Reserve, NM 87830
(505)533-6237

Willie Begay
USDI-Bureau of Indian Affairs
Truxton Canon Agency
P.O. Box 37
Valentine, AZ 86437

Dick Behan - Presenter
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Carl Beyerhelm
Forester
USDA Forest Service
Coconino National Forest
2323 E. Greenlaw Ln.
Flagstaff, AZ 86004
(602)527-7400

Robert W. Billie
Forester II
Navajo Nation Forestry Dept.
P.O. Box 230
Ft. Defiance, AZ 86504
(602)729-5165

Debbie Binnewies
USDA Forest Service
Peaks Ranger Station
5075 N. Highway 89
Flagstaff, AZ 86004
(602)526-0866

Robert Bizal
Forester
USDI-Bureau of Indian Affairs
Phoenix Area Office - Forestry
P.O. Box 10
Phoenix, AZ 85001
(602)241-2287

Elizabeth Blake
Forester
USDA Forest Service
Long Valley Ranger District
HC 31 Box 68
Happy Jack, AZ 86024
(602)527-7371

Kevin Boness
Arizona State Land Dept.
3650 Lake Mary Rd.
Flagstaff, AZ 86001
(602)774-1425

John Bradford
Forester
USDA Forest Service
Coconino National Forest
2323 E. Greenlaw Ln.
Flagstaff, AZ 86004
(602)527-7400

Richard Brown - Presenter
Arizona Game and Fish Dept.
438 Cosnino
Flagstaff, AZ 86004
(602)526-6852

Chuck Bullington - Chair
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Jon S. Bumstead
Forester
USDA Forest Service
Coconino National Forest
2323 E. Greenlaw Ln.
Flagstaff, AZ 86004
(602)527-7400

Stephen D. Butler
USDA Forest Service
Coconino National Forest
2323 E. Greenlaw Ln.
Flagstaff, AZ 86004
(602)527-7400

C

John Caffrey
USDA Forest Service
Mount Taylor Ranger District
1800 Lobo Canyon Rd.
Grants, NM 87020
(505)287-8833

Jack D. Carpenter
Silviculturist
USDA - Forest Service
Carson National Forest
P.O. Box 5810
Taos, NM 87571
(505)586-0520

Dennis Cengel
Assistant Professor
Mississippi State University
Forestry Dept.
P.O. Drawer FR
Mississippi State, MS 39762
(601)325-2792

Mary Chambers
909 W. Grand Canyon Ave.
Flagstaff, AZ 86001

Forestry Technician
USDA Forest Service
Mormon Lake Ranger District
4825 S. Lake Mary Rd.
Flagstaff, AZ 86001
(602)527-7474

David C. Chojnacki
Research Forester
USDA Forest Service
Intermountain Research Station, Forest Survey
507 25th Street
Ogden, UT 84401
(801)625-5402

Roger Clark
Chair, Committee on Proposals
Northern Arizona Natural History Assoc.
23 Pine Del Dr.
Flagstaff, AZ 86001
(602)527-6115

Wally Covington - Chair & Presenter
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Debra L. Crisp
Forestry Technician
USDA Forest Service
Coconino National Forest
2323 E. Greenlaw Ln.
Flagstaff, AZ 86004
(602)527-7400

Carol Cushing
USDA-Forest Service
Malheur National Forest
528 East Main
John Day, OR 97845
(503)575-2110

D

Sally Davidson - Student Assistant
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Robert Davis
Natural Resource Specialist
USDI Bureau of Land Management
Arizona Strip District
390N 3050E
St. George, UT 84770
(801)673-3545

Paul Declay, Jr.
Supervisory Forester
USDI-Bureau of Indian Affairs
Fort Apache Agency
P.O. Box 560
Whiteriver, AZ 85941
(602)338-4364

Daniel J. Derrick
Forester
USDA Forest Service
Coconino National Forest
2323 E. Greenlaw Ln.
Flagstaff, AZ 86004
(602)527-7400

Norris Dodd - Presenter
Arizona Game and Fish Dept.
HC 62, Box 57201
Pinetop, AZ 85935
(602)367-4281

K. Leroy Dolph
Research Forester
USDA Forest Service
Pacific SW For. & Range Expt. Stn.
2400 Washington Ave.
Redding, CA 96001
(916)246-5462

Terry Droessler - Presenter
Project Scientist
NSI Technology Services Corp.
EPA Environmental Research Lab
200 SW 35th Street
Corvallis, OR 97333
(503)757-4389

Brion Drought
Forestry Technician
USDA Forest Service
Coconino National Forest
2323 E. Greenlaw Ln.
Flagstaff, AZ 86004
(602)527-7400

Edward R. Dwan
Administrative Forester
USDI Bureau of Indian Affairs
San Carlos Agency
P.O. Box 209
San Carlos, AZ 85550
(602)475-2321

Dennis Dykstra
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

E

John H. Eavis
Forester
USDA-Forest Service
Chalender Ranger District
501 W. Bill Williams Ave.
Williams, AZ 86046
(602)635-2676

LeGrand Einbender - Student Assistant
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Leroy Elgo
Supervisory Forestry Technician
San Carlos Apache Tribe
Forestry Program
P.O. Box 0
San Carlos, AZ 85550
(602)475-2329

Celeste Epperly
Forestry Technician
USDA Forest Service
Peaks Ranger Station
5075 N. Highway 89
Flagstaff, AZ 86004
(602)526-0866

Charles Ester
Senior Hydrologist
Salt River Project
P.O. Box 52025
Phoenix, AZ 85072-2025
(602)236-5087

F

Mary Lou Fairweather
Pathologist
USDA Forest Service
Coconino National Forest
2323 E. Greenlaw Ln.
Flagstaff, AZ 86004
(602)527-7358

James H. Fitch
Forester
USDA - Forest Service
Carson National Forest
P.O. Box 558
Taos, NM 87571
(505)758-6200

Bruce Fox - Presenter
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Kel Fox - Keynote Speaker
Two Bar Cattle Co.
Munds Park, AZ 86017
(602)286-1094

Pete Fule - Student Assistant
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

G

Jerry D. Gaither
Supervisory Forester
USDA Forest Service
Coconino National Forest
2323 E. Greenlaw Ln.
Flagstaff, AZ 86004
(602)527-7400

Sharon Galbreath
Chair
Sierra Club, Plateau Group
P.O. Box 15
Flagstaff, AZ 86002
(602)774-1571

Dave Garrett - Presenter
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Heather Green
USDA Forest Service
Mormon Lake Ranger District
4825 S. Lake Mary Rd.
Flagstaff, AZ 86001
(602)527-7474

Chuck Grier - Presenter
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Bill Groman
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Tom Gross - Presenter
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Craig Gordon
Forester II
Navajo Nation Forestry Dept.
P.O. Box 230
Ft. Defiance, AZ 86504
(602)729-5165

H

Pat Hall - Presenter
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Ron C. Hamilton
Regional Geneticist
USDA Forest Service
Region 4
Federal Building
324 25th Street
Ogden, UT 84401
(801)625-5525

William B. Hammond
Forester
USDA Forest Service
Coyote Ranger District
Coyote, NM 87012
(505)638-5547

Bob Hamre - Editor
USDA - Forest Service
Rocky Mountain Station
240 W. Prospect
Fort Collins, CO 80526-2098
(303)498-1282

Paula Harger
Forestry Trainee
USDA Forest Service
Coconino National Forest
2323 E. Greenlaw Ln.
Flagstaff, AZ 86004
(602)527-7400

Bruce J. Higgins
Forester
USDA Forest Service
Kaibab National Forest
501 W. Bill Williams Ave.
Williams, AZ 86046
(602)635-2676

Bill Holmes
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Terry Hudgins
President
Arizona Water Resources Committee
Arizona Public Service
P.O. Box 53999
Phoenix, AZ 85072
(602)250-2878

Philip K. Hunkins
Land Management Planner
USDA - Forest Service
Kaibab National Forest
800 S. 6th Street
Williams, AZ 86046
(602)635-2681

J

Richard M. Jeffers
Regional Geneticist
USDA - Forest Service
Region 3
517 Gold Ave., SW
Albuquerque, NM 87102
(505)842-3480

Ralph Johnson - Moderator
Forester
USDA Forest Service
3825 E. Mulberry
Ft. Collins, CO 80524
(303)482-8950

K

John Keane - Moderator
Manager, Surface Water Resources
Salt River Project
P.O. Box 52025
Phoenix, AZ 85072-2025
(602)236-5087

John H. Keenan
Forester
USDA - Forest Service
Carson National Forest
P.O. Box 558
Taos, NM 87571
(505)758-6200

Dennis Kingsbury
Timber Manager
Stone Forest Industries
825 E. Butler Ave.
Flagstaff, AZ 86001
(602)774-4511

David A. Koehler - Presenter
Area Supervisory Range Conservationist
USDI - Bureau of Indian Affairs
P.O. Box M
Window Rock, AZ 86515
(602)871-5151

Bruce Koyiyumtewa
Silviculturist
USDA Forest Service
Long Valley Ranger District
HC 31 P.O. Box 68
Happy Jack, AZ 86024
(602)354-2216

Mike Kremeke
USDA Forest Service
Tusayan Ranger District
P.O. Box 3088
Tusayan, AZ 86023

Erv Kulosa
Tribal Forester
White Mountain Apache Nation
P.O. Box 700
Whiteriver, AZ 85941
(602)338-4931

Ernest A. Kurmes - Presenter
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

L

Bob Larson
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3-31

William F. Laudenslayer Jr.
Wildlife Biologist
USDA Forest Service
PSW, Tahoe National Forest
Highway 40 & Coyote St.
Nevada City, CA 95959
(916)265-4531

Frank Lenning - Student Assistant
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Dan L. Lentz
Silviculturist
USDA Forest Service
Jemez Ranger District
P.O. Box 98
Jemez Springs, NM 87025
(505)829-3535

Yiquin Lin - Presenter
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Yan Linhart - Presenter
Professor
University of Colorado
Dept. of Biology
P.O. Box 334
Boulder, CO 80309
(303)492-8301

Gary S. Lukas
Silviculturist
USDA Forest Service
P.O. Box 170
Reserve, NM 87830
(505)533-6231

M

Anita J. MacFarlane
Co-chair, Conservation Committee
Northern Arizona Audubon Society
505 Morgan Road
Sedona, AZ 86336
(602)282-4063

Susan MacVean
Wildlife Biologist
USDA Forest Service
Kaibab National Forest
Box 248
Fredonia, AZ 86022
(602)643-7395

Michael Manthei
Forester
USDA Forest Service
Coconino National Forest
2323 E. Greenlaw Ln.
Flagstaff, AZ 86004
(602)527-7400

Jonathan Martin
The Navajo Nation
205 Wyatt St.
Gallup, NM 87301

Timothy G. McGann
Forester
USDA Forest Service
Kaibab National Forest
501 W. Bill Williams Ave.
Williams, AZ 86046
(602)635-2676

Tricia McGraw
Water Resources Specialist
Arizona Dept. of Water Resources
15 S. 15th Ave.
Phoenix, AZ 85007
(602)542-1546

Debra K. McGuin
535 East Comanche St.
Flagstaff, AZ 86001

Chuck McHugh
Forestry Technician
USDA Forest Service
Coconino National Forest
2323 E. Greenlaw Ln.
Flagstaff, AZ 86004
(602)527-7400

Joel McMillin - Presenter
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Jim McRae
Forester
San Carlos Apache Tribe
Forestry Program
P.O. Box 0
San Carlos, AZ 85550
(602)475-2329

Alvin Medina
USDA - Forest Service
Rocky Mountain Station
Forestry Sciences Laboratory
Arizona State University
Tempe, AZ 85287-1304
(602)379-4365

Scott Meneely
Forester
USDI Bureau of Indian Affairs
San Carlos Agency
P.O. Box 209
San Carlos, AZ 85550
(602)475-2329

Greg Miller
Soil Scientist
USDA - Forest Service
Coconino National Forest
2323 E. Greenlaw Lane
Flagstaff, AZ 86004
(602)527-7378

Jeffrey Miller - Presenter
Environmental Consultant
7045 NW Grandview Dr.
Corvallis, OR 97330

Chuck Minor
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Cheryl Mollohan - Presenter
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Margaret Moore - Chair
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Cary Morris
Forestry Technician
USDA Forest Service
Mormon Lake Ranger District
4825 S. Lake Mary Rd.
Flagstaff, AZ 86001
(602)527-7474

Donald Muise
Forester
USDA Forest Service
Coconino National Forest
2323 E. Greenlaw Ln.
Flagstaff, AZ 86004

Terry L. Myers
Wildlife Biologist
USDA - Forest Service
Lakeside Ranger District
Rt. 3, Box B-50
Lakeside, AZ 85929
(602)368-5111

N

Sandra J. Nagiller
Wildlife Biologist
USDA Forest Service
Coconino National Forest
2323 E. Greenlaw Ln.
Flagstaff, AZ 86004
(602)527-7400

O

Marvin M. Olson
Forester
USDI - Bureau of Indian Affairs
Jicarilla Agency
Branch of Forestry
P.O. Box 167
Dulce, NM 87528
(505)759-3960

P

Dave Patton - Presenter & Moderator
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Ace H. Peterson - Presenter
Conservation Chairman
Arizona Wildlife Federation
101 W. Cherry Ave.
Flagstaff, AZ 86001
(602)779-6911

Daniel E. Pitterle
Forester I
Navajo Nation Forestry Dept.
P.O. Box 230
Ft. Defiance, AZ 86504
(602)729-5165

Joe Price
USDA Forest Service
Mount Taylor Ranger District
1800 Lobo Canyon Rd.
Grants, NM 87020

R

Dee Randall
Forester
San Carlos Apache Tribe
Forestry Program
P.O. Box 0
San Carlos, AZ 85550
(602)475-2329

Tammy Randall-Parker
Wildlife Tech.
USDA Forest Service
Peaks Ranger Station
5075 N. Highway 89
Flagstaff, AZ 86004
(602)526-0866

Hildy Reiser
District Wildlife Biologist
USDA-Forest Service
P.O. Box 478
Overgaard, AZ 85933
(602)535-4481

Mert Richards - Presenter
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

David M. Robbins
535 East Comanche St.
Flagstaff, AZ 86001

John W. Russell
Director, Land Management Planning
USDA - Forest Service
Southwestern Region
517 Gold Ave., SW
Albuquerque, NM 87102
(505)842-3210

Bernie Ryan
Timber Management Officer
USDI - Bureau of Indian Affairs
Jicarilla Agency
Branch of Forestry
P.O. Box 167
Dulce, NM 87528
(505)759-8967

Patrick Ryan
Wildlife Biologist
Navajo Fish & Wildlife
P.O. Box 1836
Window Rock, AZ 86515
(602)871-5338

S

Ing. Juan Manuel Cassian Santos
Director
Forest Administration Unit #6 "El Salto"
Calle Coronado #834
Durango, DGO
MEXICO
(181)3-3079

John P. Schafer
USGS - Retired
508 W. Philomena Dr.
Flagstaff, AZ 86001
(602)779-0236

Jacob Schlapfer - Student Assistant
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Keith E. Severson - Presenter
Project Leader
Rocky Mountain Station
Forestry Sciences Lab
Arizona State University
Tempe, AZ 85287-1304
(602)261-4365

Larry Simpson
Forestry Tech.
USDA Forest Service
Coconino National Forest
2323 E. Greenlaw Ln.
Flagstaff, AZ 86004
(602)527-7400

Edward Smith
Coconino Forest Watch
P.O. Box 1424
Flagstaff, AZ 86004
(602)527-6886

Rick Stahn
Silviculturist
USDA Forest Service
Mormon Lake Ranger District
4825 S. Lake Mary Rd.
Flagstaff, AZ 86001
(602)527-7474

Bill Stansfield - Presenter
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Dennis Sundie
Planning Division Chief
Arizona Dept. of Water Resources
15 S. 15th Ave.
Phoenix, AZ 85007
(602)542-1546

Peggy Swift - Student Assistant
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

T

Aregai Tecle - Presenter & Chair
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Charles E. Thomas - Presenter
Research Forester
USDA - Forest Service
Southern Forest Experiment Station
701 Loyola Ave.
New Orleans, LA 70118
(504)589-4545

Steve Thomas
Forester
USDI - Bureau of Indian Affairs
Jicarilla Agency
Branch of Forestry
P.O. Box 167
Dulce, NM 87528
(505)759-3966

Frankie Thompson
Forester I
Navajo Nation Forestry Dept.
P.O. Box 230
Ft. Defiance, AZ 86504
(602)729-5165

Borys Tkacz - Presenter
Zone Leader
USDA Forest Service
Coconino National Forest
2323 E. Greenlaw Ln.
Flagstaff, AZ 86004
(602)527-7357

William D. Torgersen
Forester
USDI - Bureau of Land Management
Washington Office (230)
18 and C Streets, NW
Washington, DC 20240
(202)653-8864

Ron Trosper
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Walter J. Tucker
Range Conservationist
USDA Forest Service
Coconino National Forest
2323 E. Greenlaw Ln.
Flagstaff, AZ 86004
(602)527-7357

V

Warren Vigil
Forestry Tech.
USDI - Bureau of Indian Affairs
Jicarilla Agency
Branch of Forestry
P.O. Box 167
Dulce, NM 87528
(505)759-3961

W

Richard L. Wadleigh
Wildlife Program Manager
USDA Forest Service
Region 3
517 Gold Ave., SW
Albuquerque, NM 87102
(505)842-3263

Mike Wagner - Presenter & Moderator
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Gene P. Waldrip
District Ranger
USDA Forest Service
Kaibab National Forest
501 W. Bill Williams Ave.
Williams, AZ 86046
(602)635-2676

Greg Wallace
Division Chief
Arizona Dept. of Water Resources
15 S. 15th Ave.
Phoenix, AZ 85007
(602)542-1546

Noel E. Walsh
Wildlife Biologist
USDA Forest Service
Kaibab National Forest
800 S. Sixth St.
Williams, AZ 86046
(602)635-2681

Donald R. Weaver
Silviculturist
USDA Forest Service
Reserve Ranger District
Box 170
Reserve, NM 87830
(505)533-6231

Gary Weber
USDA Forest Service
Tusayan Ranger District
P.O. Box 3088
Tusayan, AZ 86023

W. J. Wessell

Forester
USDA-Forest Service
Tonto National Forest
P.O. Box 5348
Phoenix, AZ 85010
(602)225-5255

Craig Wilcox
Forestry Program Director
San Carlos Apache Tribe
Forestry Program
P.O. Box 0
San Carlos, AZ 85550
(602)475-2387

Jon T. Williams
Forester
USDA-Forest Service
Apache-Sitgreaves N.F.
P.O. Box 640
Springerville, AZ 85938
(602)338-4364

Jill L. Wilson
Entomologist
USDA Forest Service
Coconino National Forest
2323 E. Greenlaw Ln.
Flagstaff, AZ 86004
(602)527-7358

Sam J. Wolfskill
Forester
USDA-Forest Service
Coconino National Forest
2323 E. Greenlaw Lane
Flagstaff, AZ 86004
(602)527-7425

Don Wommack
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Brent Wood - Presenter
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031

Craig L. Woods
USDA-Forest Service
Malheur National Forest
528 East Main
John Day, OR 97845
(503)575-2110

Z

Lan Zheng - Student Assistant
School of Forestry
Northern Arizona University
P.O. Box 4098
Flagstaff, AZ 86011
(602)523-3031





Rocky
Mountains



Southwest



Great
Plains

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

The Rocky Mountain Station is one of eight regional experiment stations, plus the Forest Products Laboratory and the Washington Office Staff, that make up the Forest Service research organization.

RESEARCH FOCUS

Research programs at the Rocky Mountain Station are coordinated with area universities and with other institutions. Many studies are conducted on a cooperative basis to accelerate solutions to problems involving range, water, wildlife and fish habitat, human and community development, timber, recreation, protection, and multiresource evaluation.

RESEARCH LOCATIONS

Research Work Units of the Rocky Mountain Station are operated in cooperation with universities in the following cities:

Albuquerque, New Mexico
Flagstaff, Arizona
Fort Collins, Colorado*
Laramie, Wyoming
Lincoln, Nebraska
Rapid City, South Dakota
Tempe, Arizona

*Station Headquarters: 240 W. Prospect Rd., Fort Collins, CO 80526